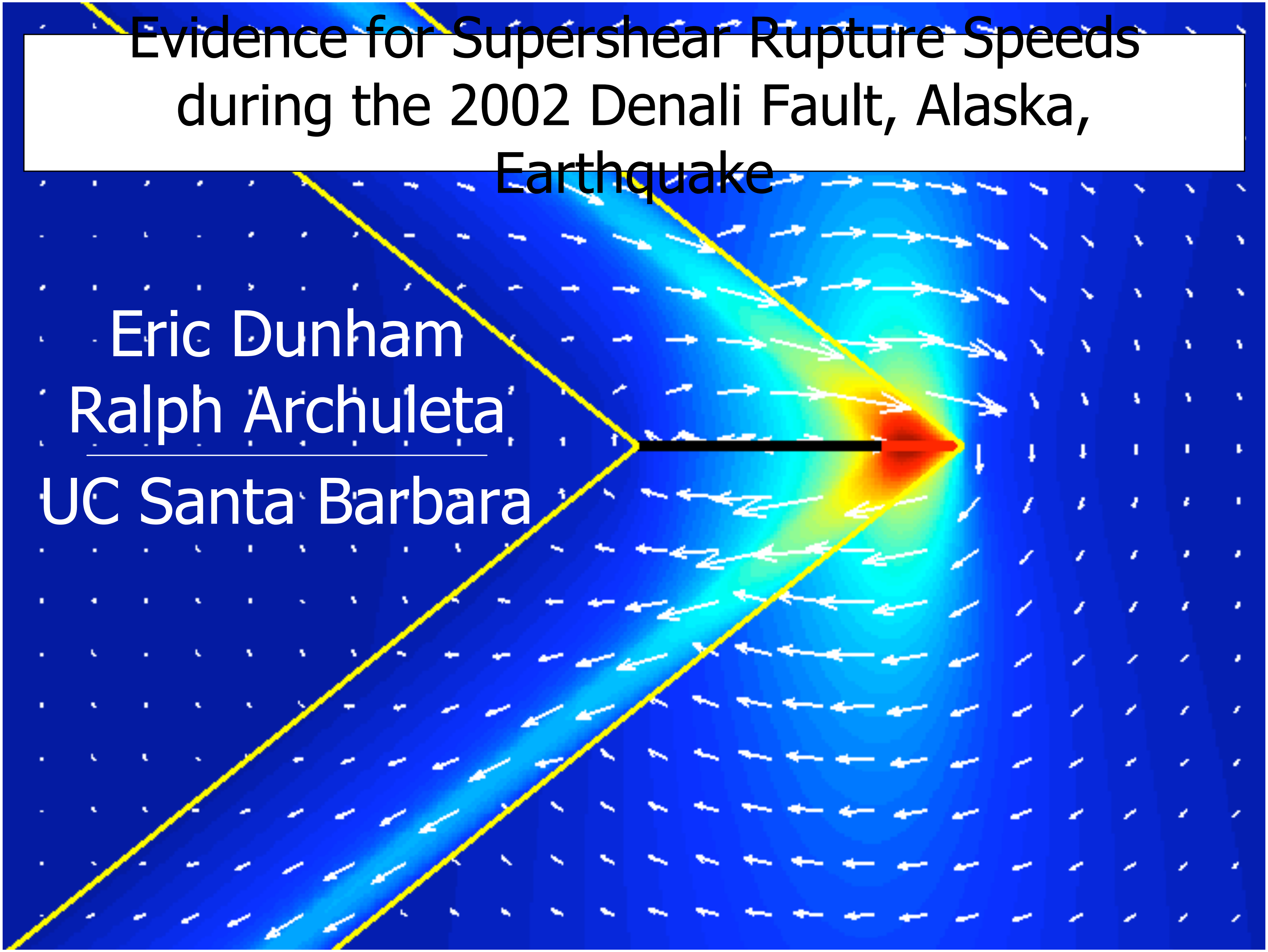
Evidence for Supershear Rupture Speeds during the 2002 Denali Fault, Alaska, Earthquake

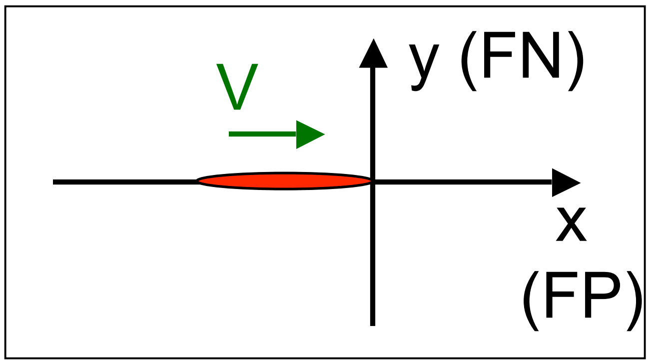


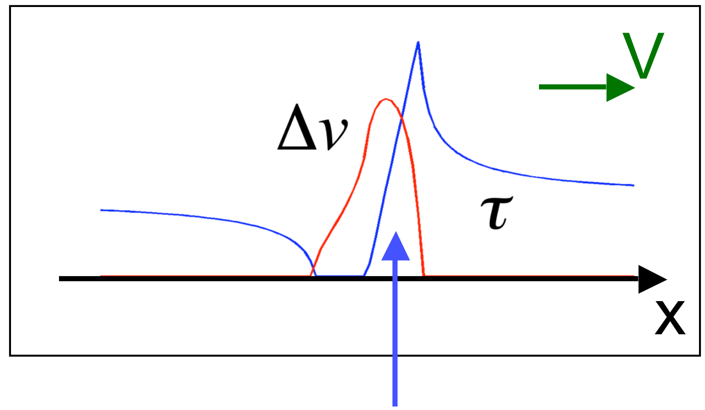
Eric Dunham
Ralph Archuleta

UC Santa Barbara

Ground Motion from Dynamic Rupture Models

Steady-state slip pulse in 2D

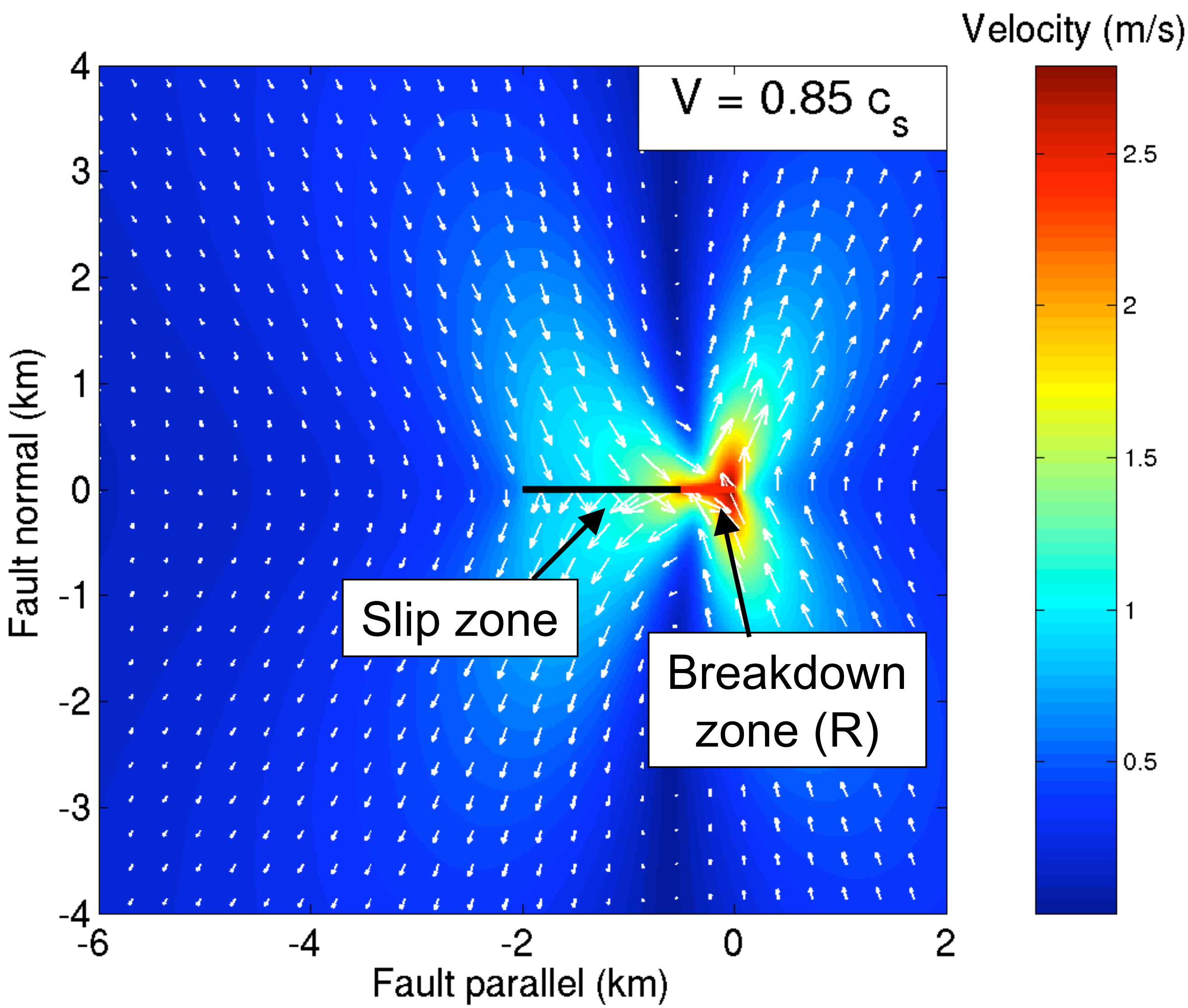




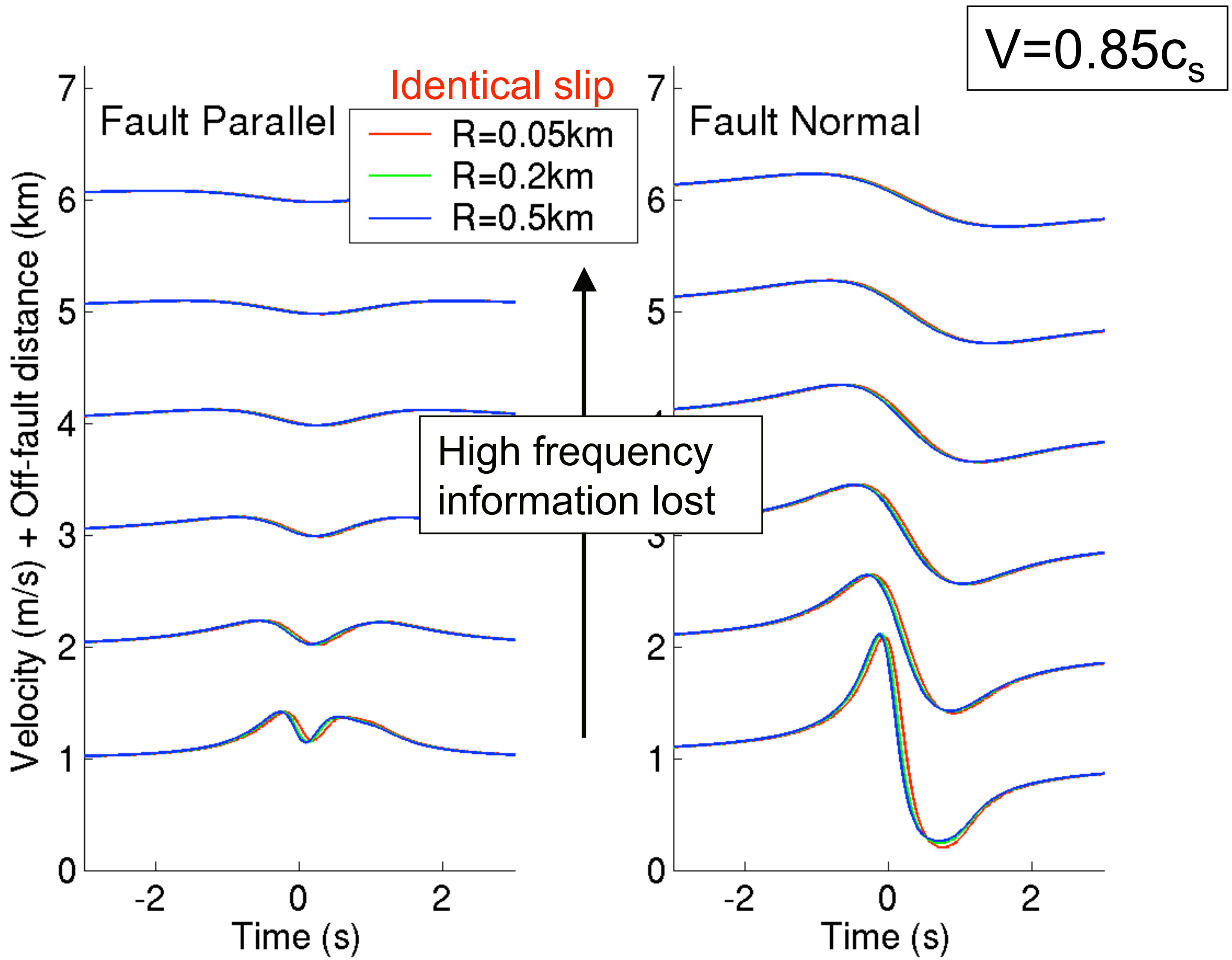
Dynamic (specify shear traction in slip zone)

Analytical expressions for velocity and stress fields, both on and off of the fault, have been derived (Broberg, 1978; Freund, 1979; Broberg, 1989; Rice et al., 2004; Dunham, 2004)

Velocity Field for Sub-Rayleigh Rupture



Synthetic Seismograms: Sub-Rayleigh



What properties of the rupture process are measurable?

More than a few km from the fault,
ground motion is only sensitive to:

Kinematic parameters

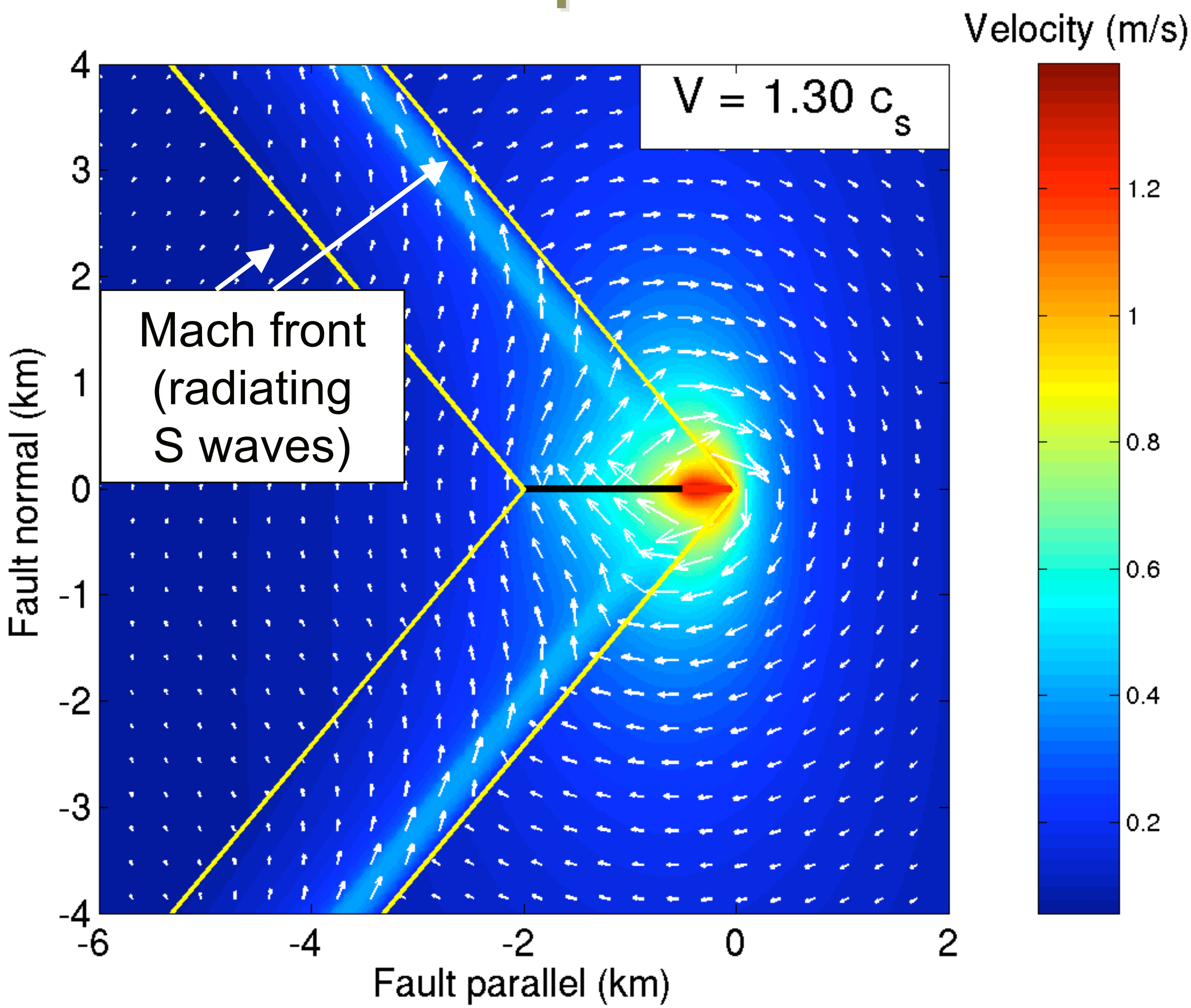
1. rupture speed V
2. slip zone length L (or rise time)
3. final slip
4. fracture energy G (indirectly…)

Not sensitive to:

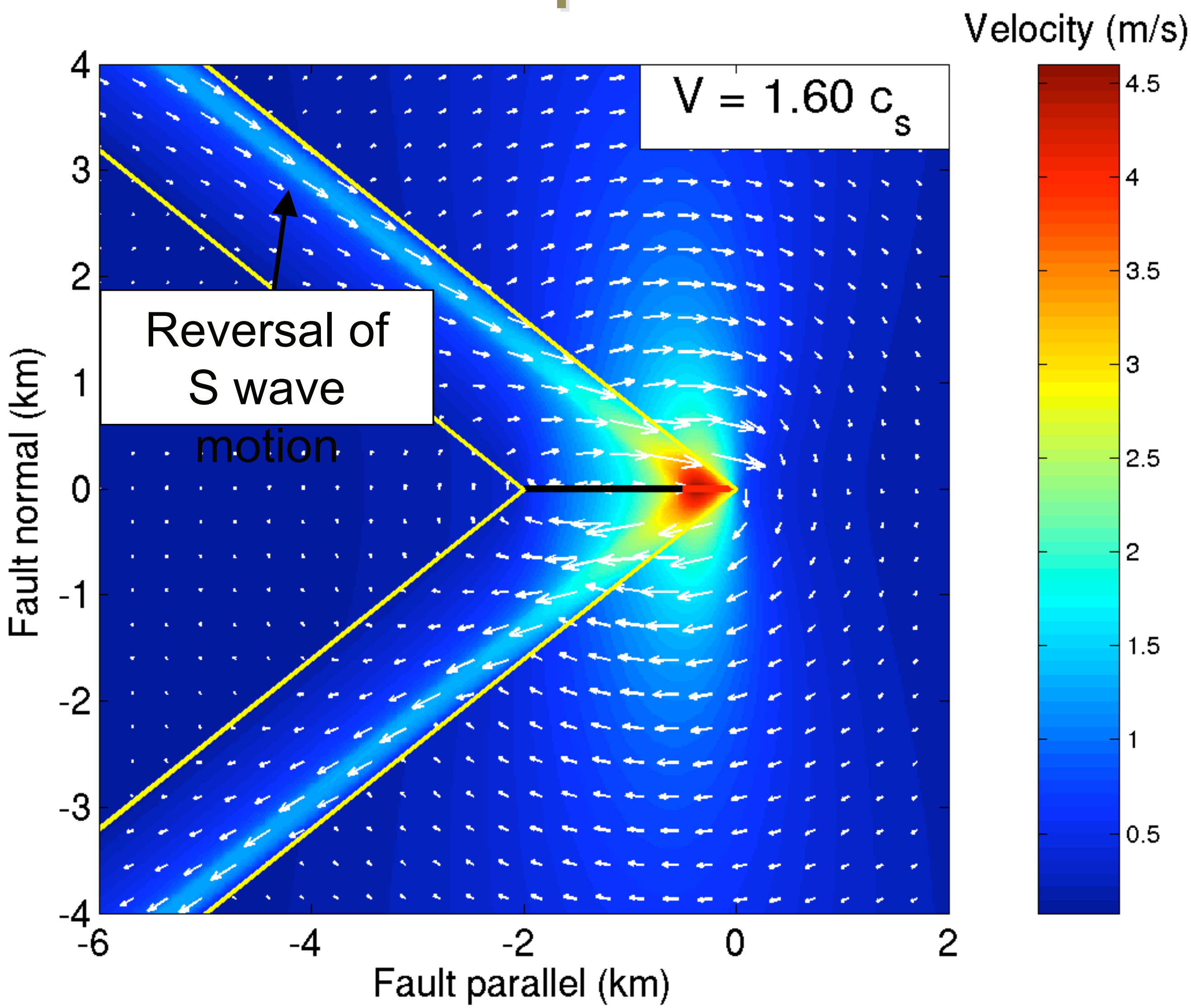
1. breakdown zone length R

This explains why kinematic models have been so successful and is bad news for seismologists interested in dynamics…

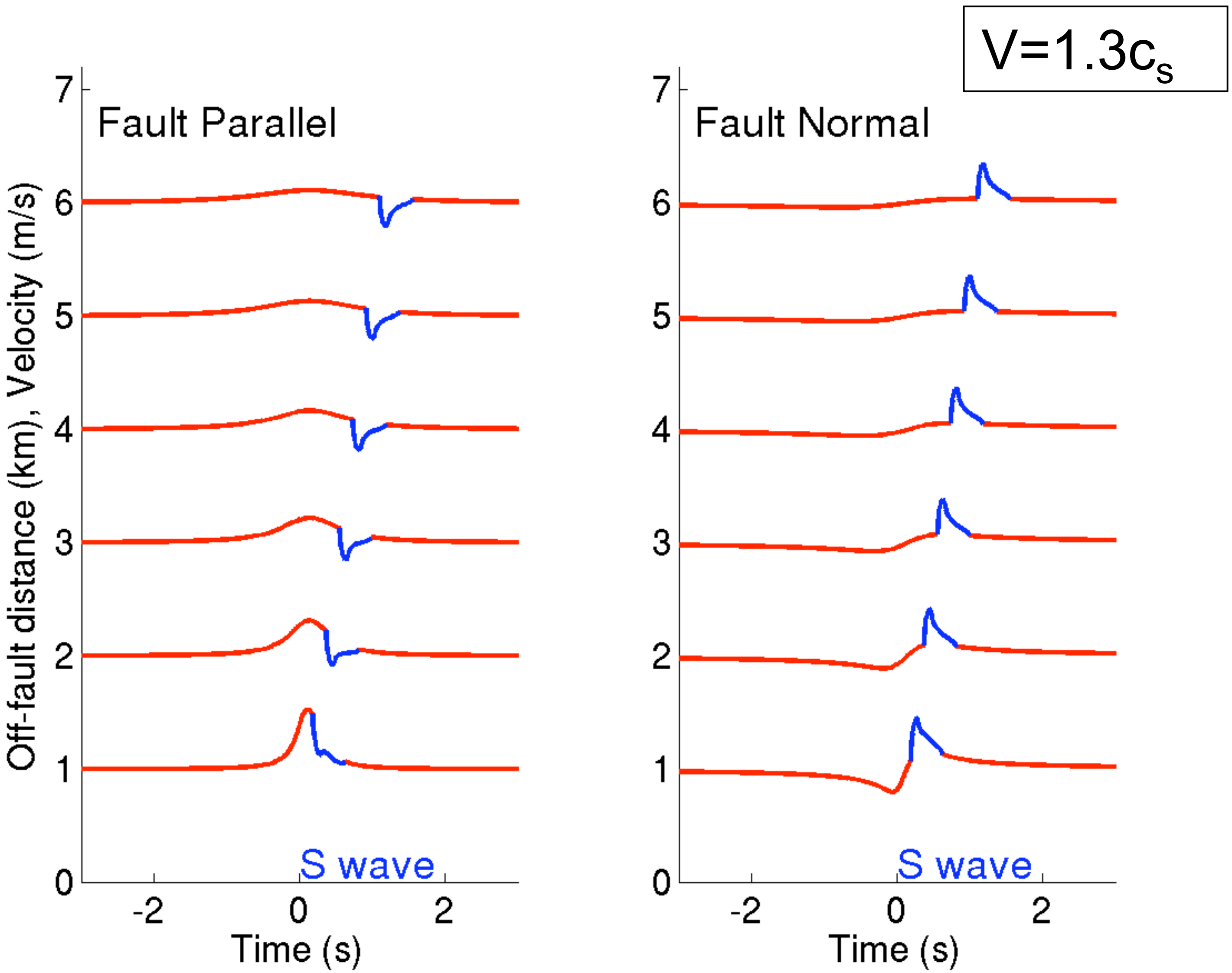
Velocity Field for Intersonic Rupture



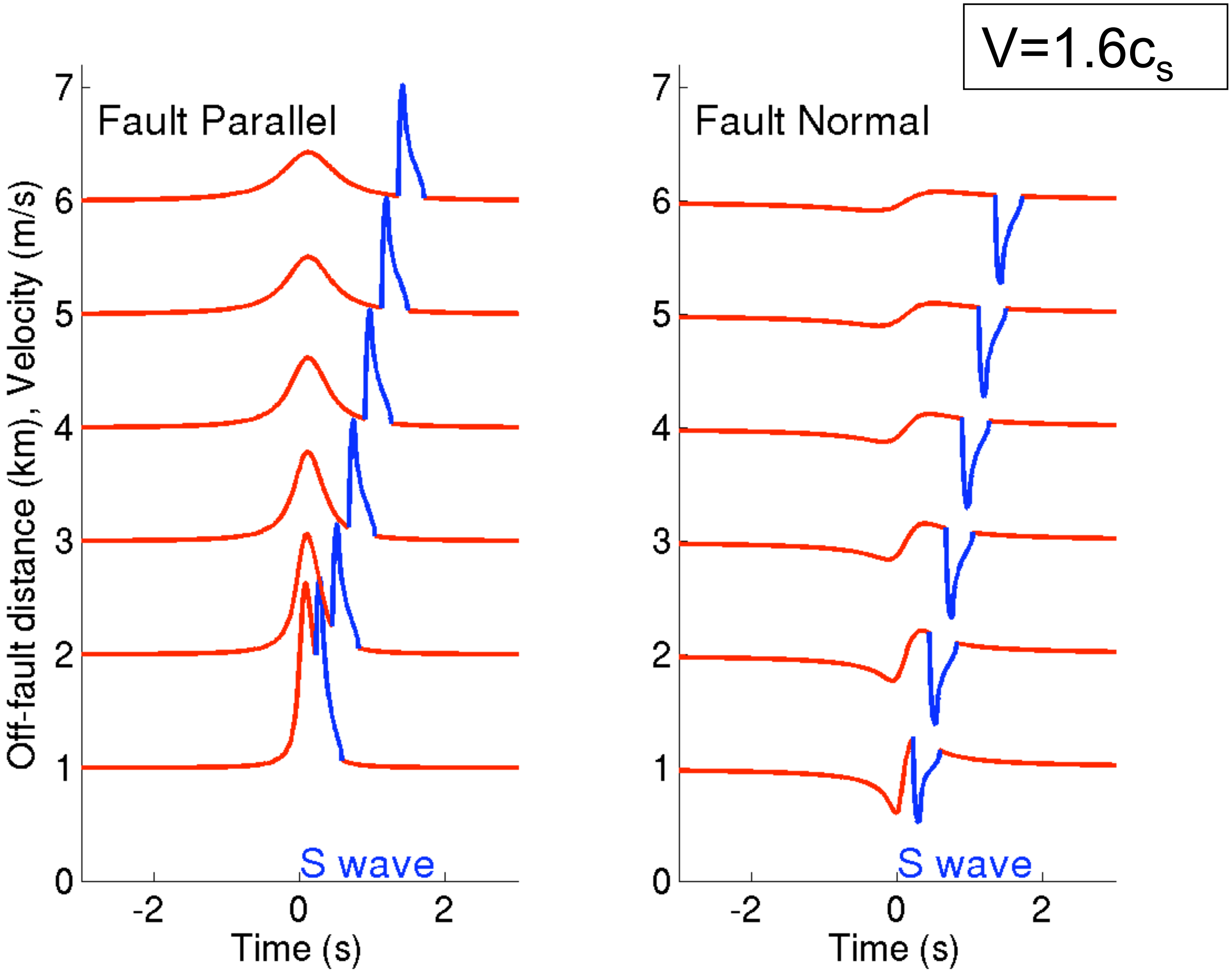
Velocity Field for Intersonic Rupture



Observational Signature



Observational Signature



One can analytically show that:

Every S wave velocity and stress component recorded away from the fault traces the exact slip velocity history on the fault!

→ Very different attenuation relationships
for supershear ruptures

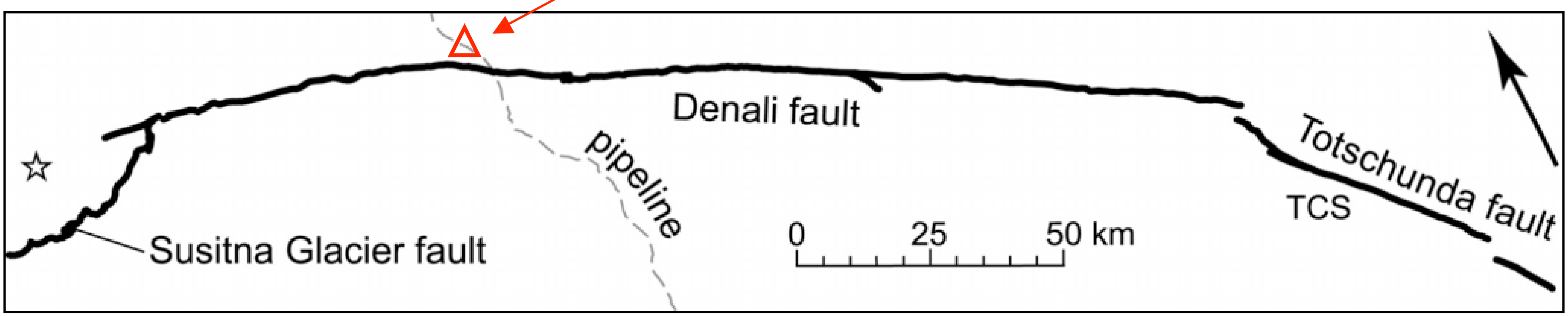
(Dunham, submitted to *GRL*, 2004)
open-source Fortran code to be released soon

2002 Denali Fault Earthquake

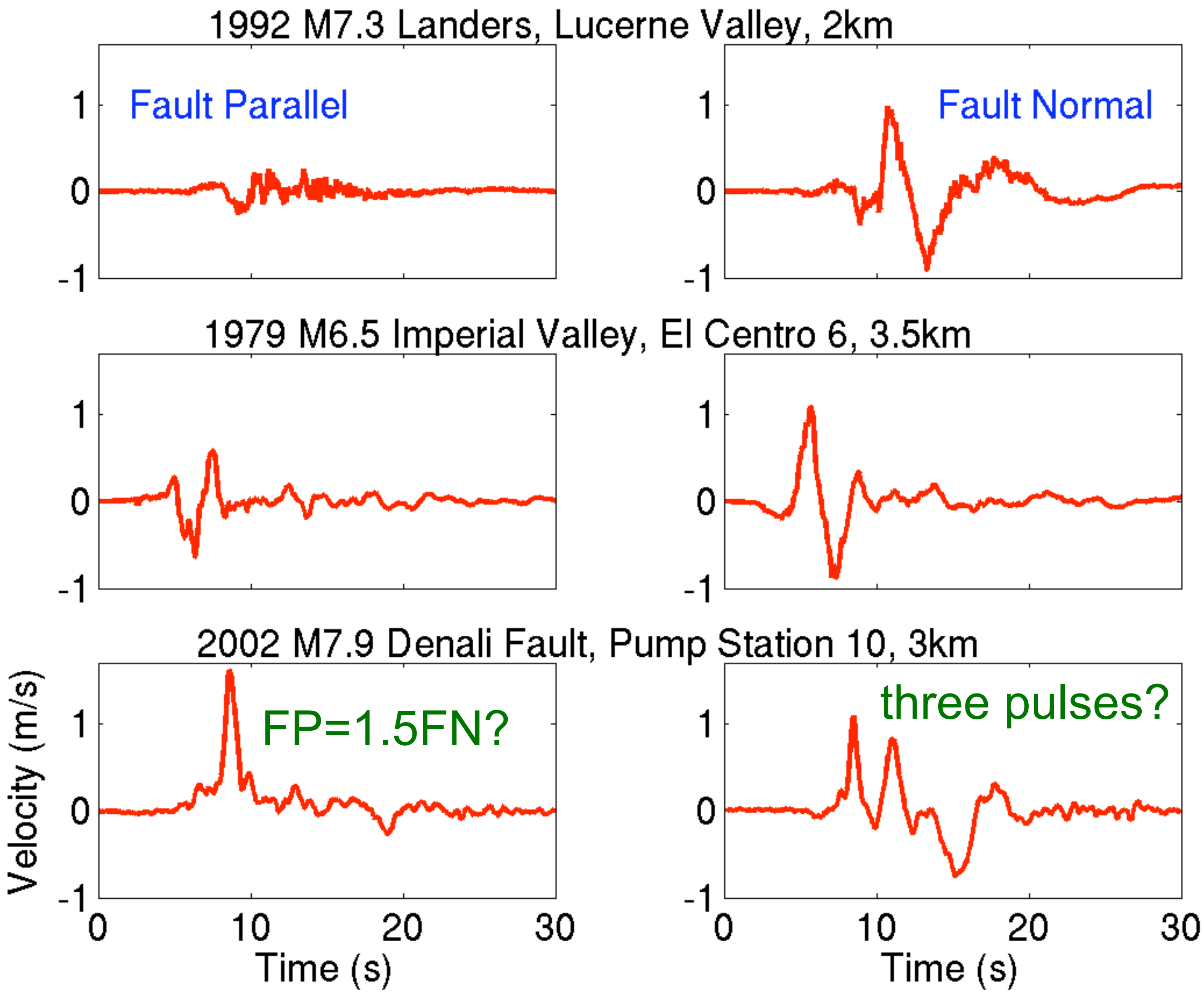
courtesy USGS

Pump Station 10 (PS10)

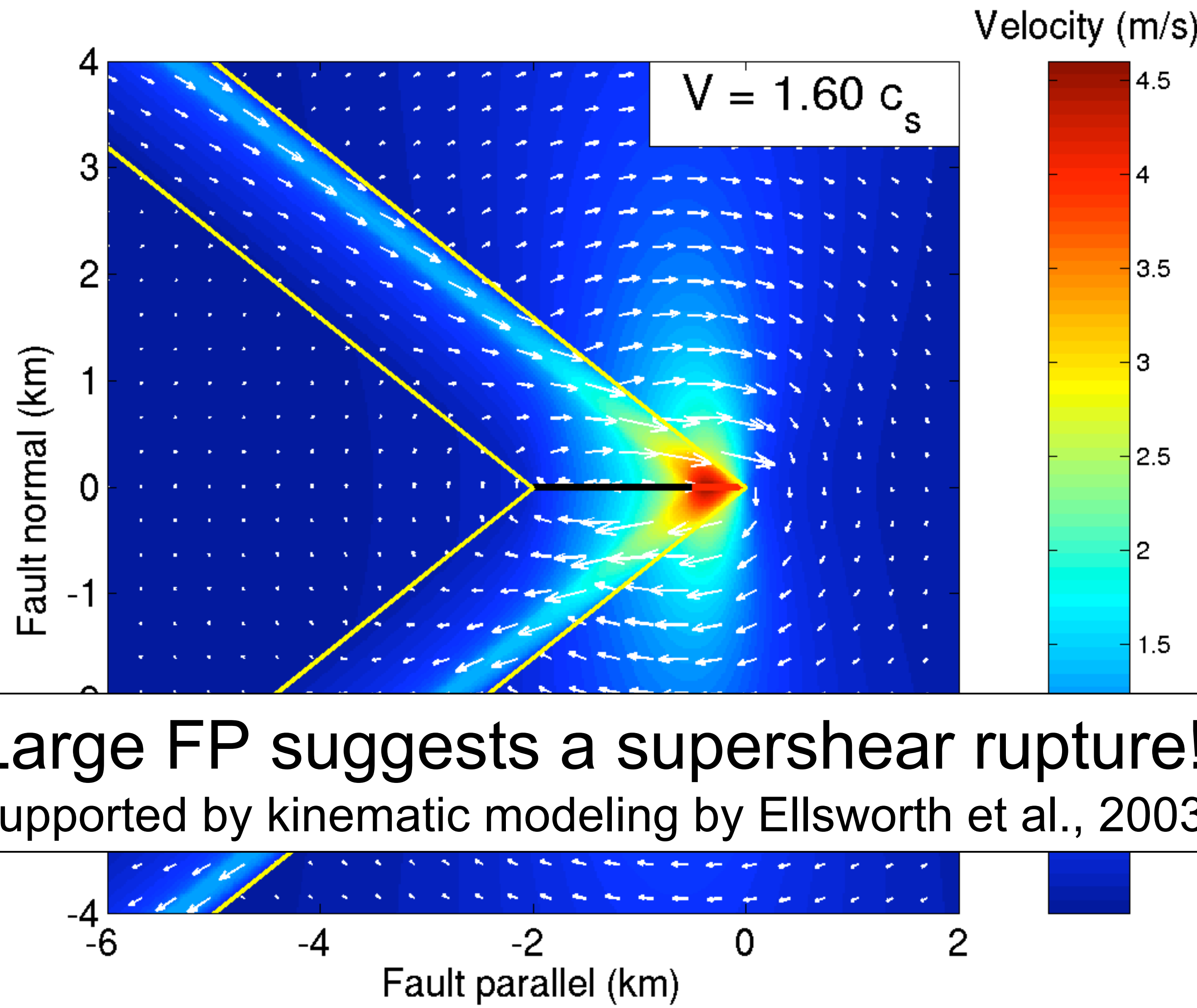
3km N of fault



The Puzzle


1992 M7.3 Landers, Lucerne Valley, 2km
Fault Parallel
Fault Normal
1979 M6.5 Imperial Valley, El Centro 6, 3.5km
2002 M7.9 Denali Fault, Pump Station 10, 3km
FP=1.5FN?
three pulses?
Velocity (m/s)
Time (s)
Time (s)
1
0
-1
0
10
20
30

FP/FN and Supershear Ruptures

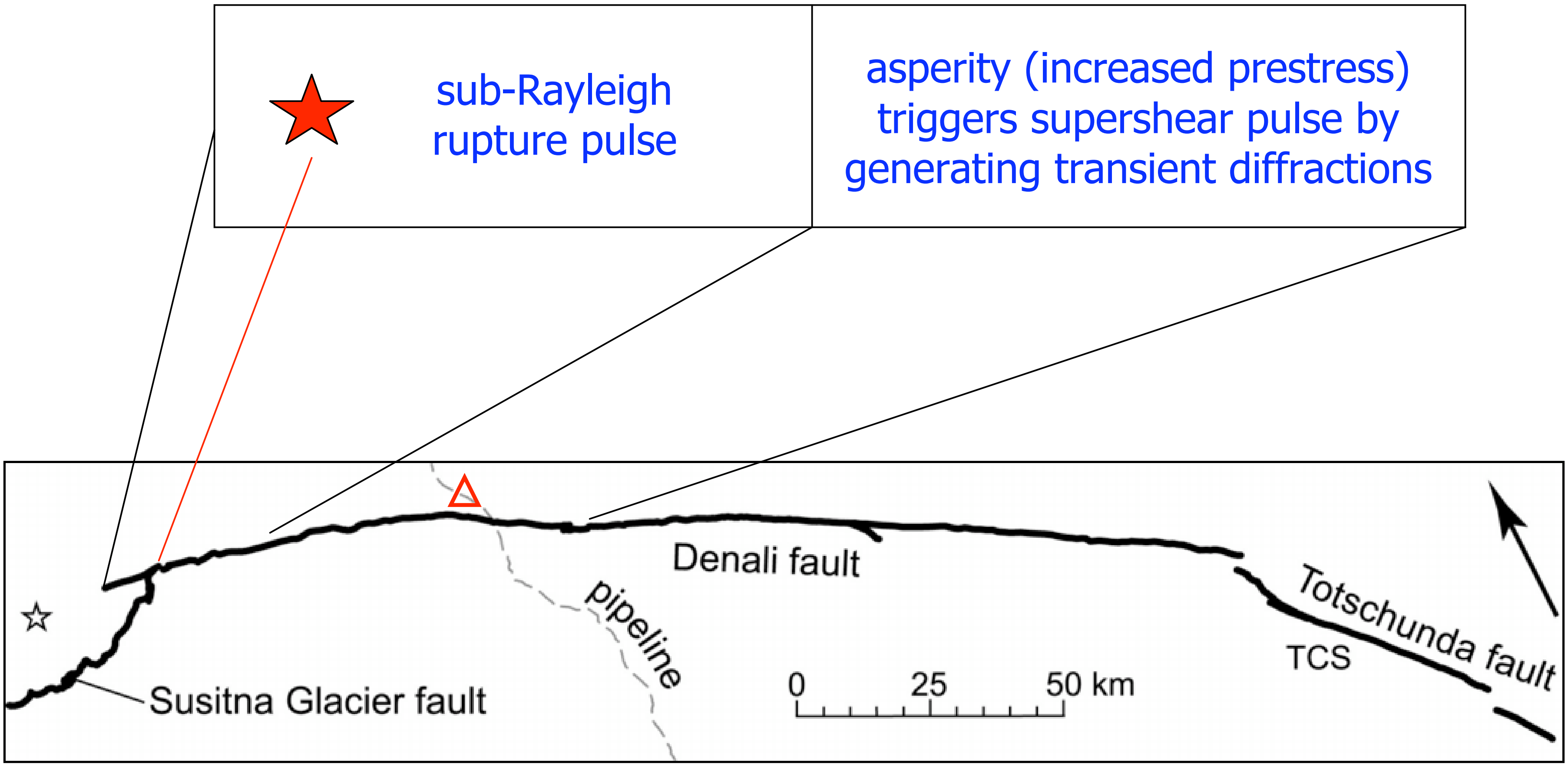


Large FP suggests a supershear rupture!

(supported by kinematic modeling by Ellsworth et al., 2003)

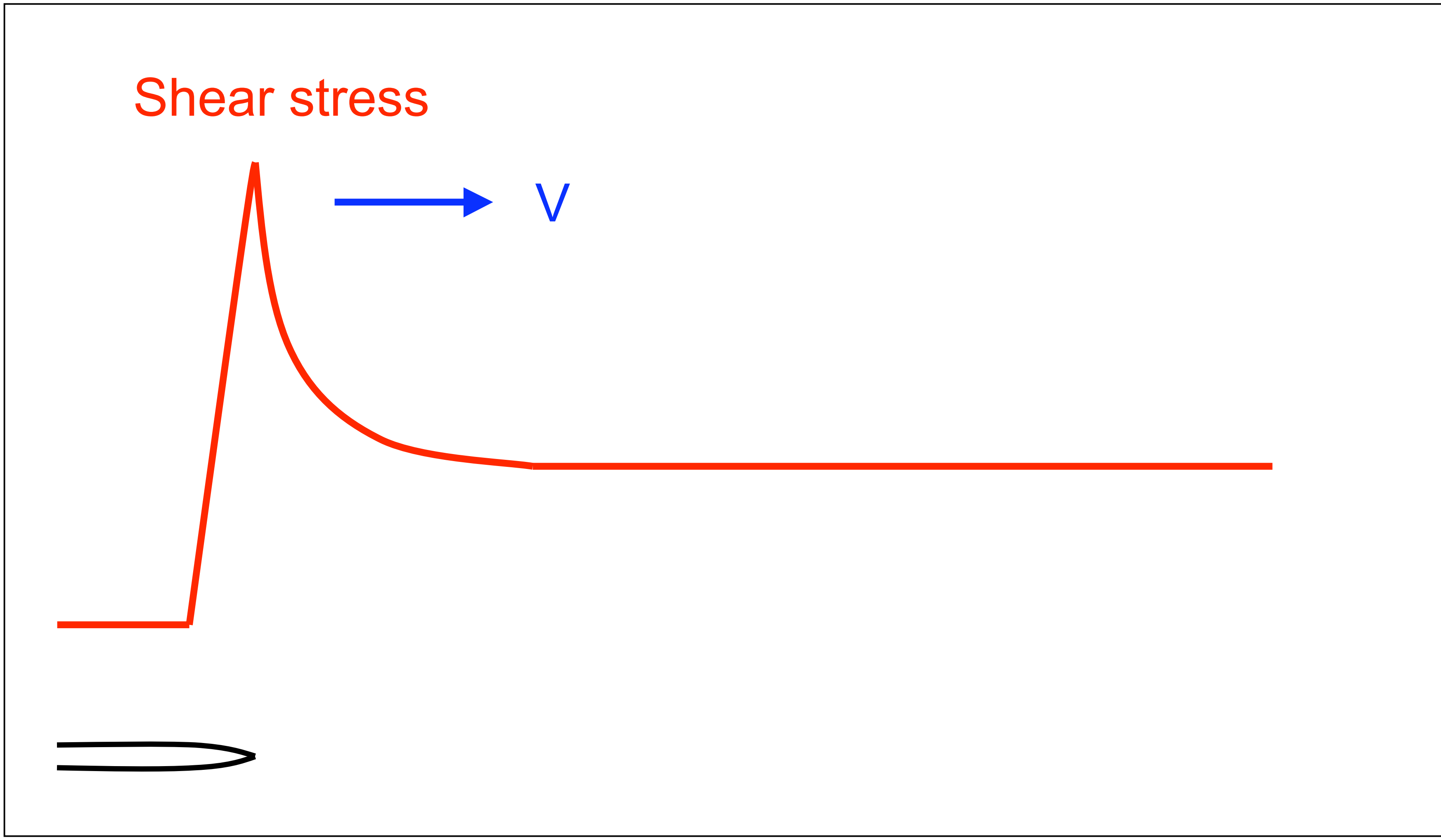
A Spontaneous Dynamic Rupture Model

Extremely simple model – no depth dependence

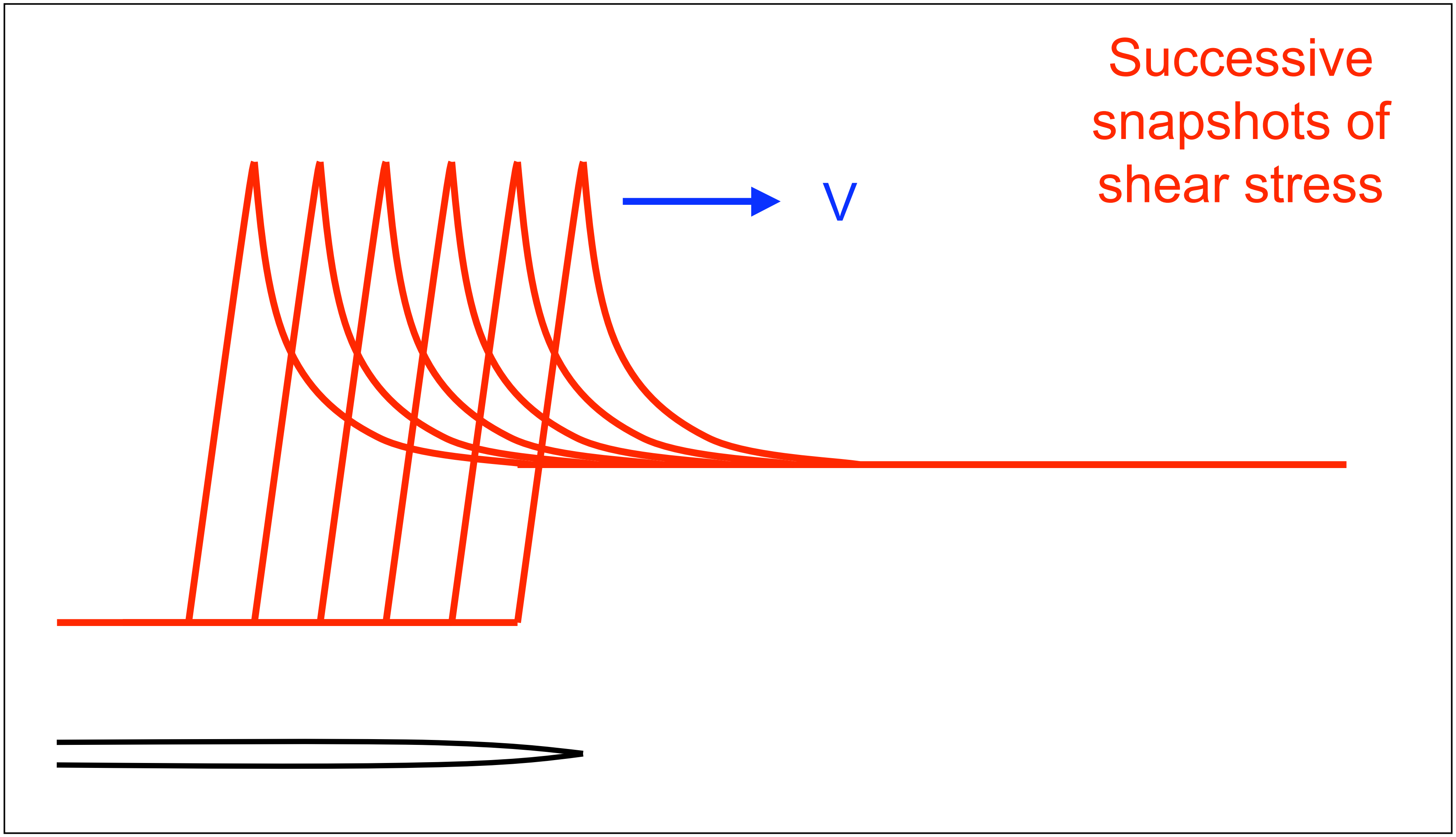


(Dunham and Archuleta, *BSSA*, 2005)

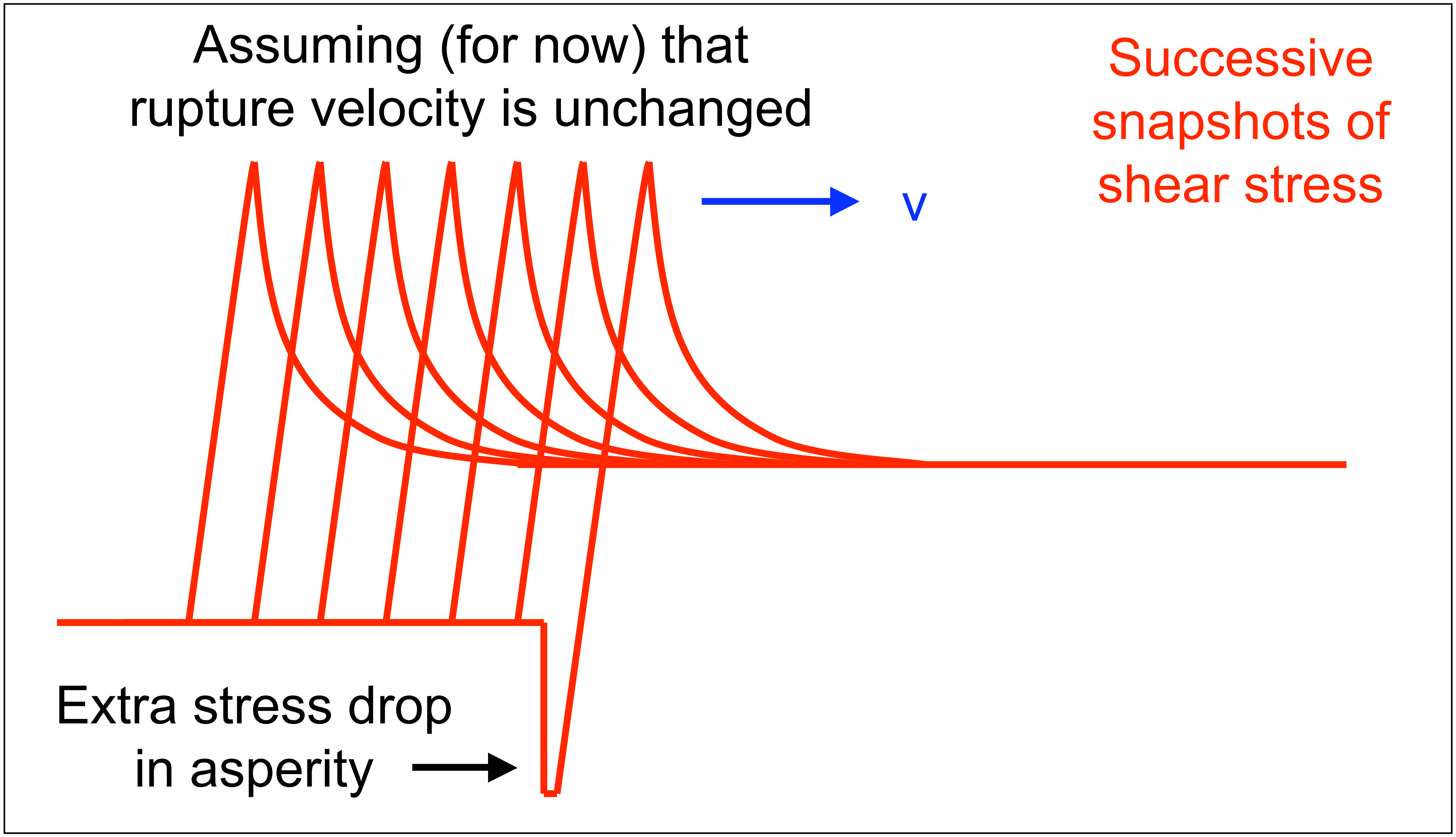
Rupture of an Asperity:
1. Steady state rupture



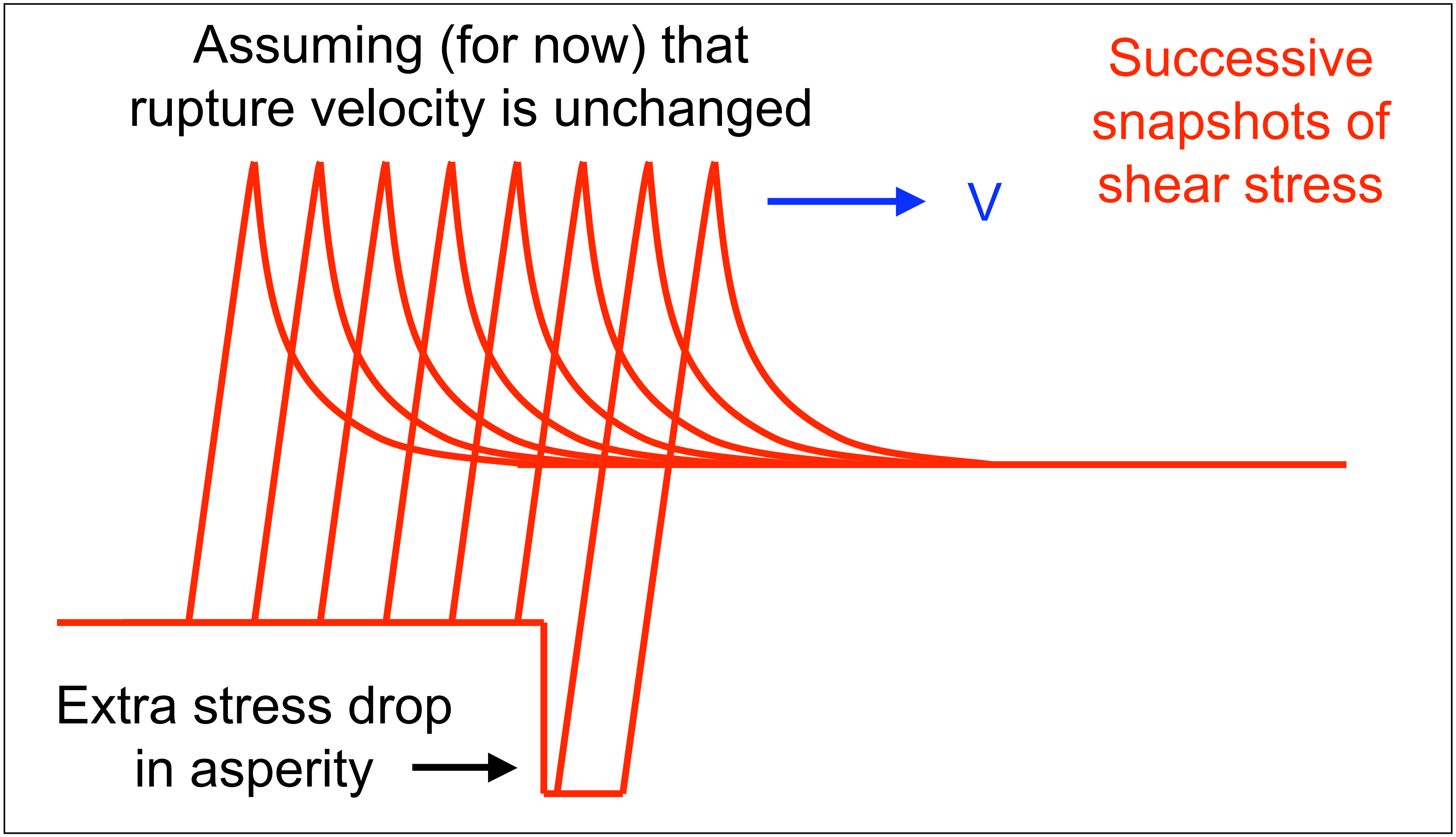
Rupture of an Asperity:
1. Steady state rupture



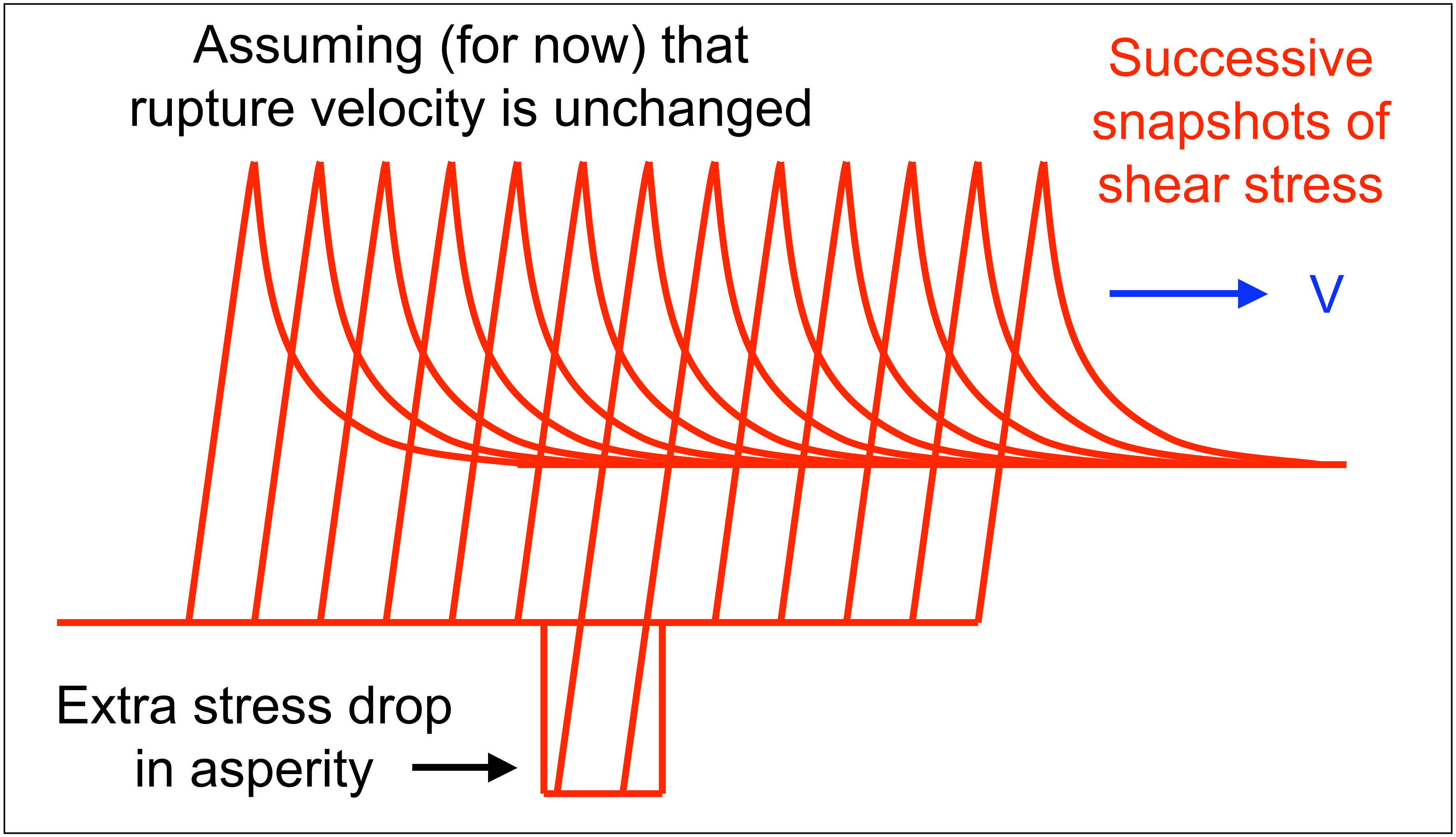
Rupture of an Asperity:
2. Extra stress drop in asperity



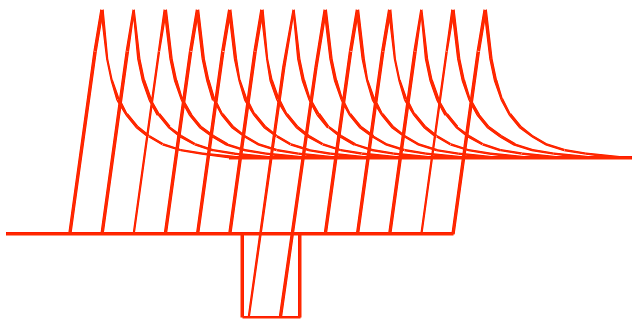
Rupture of an Asperity: 2. Extra stress drop in asperity



Rupture of an Asperity: 2. Extra stress drop in asperity



Rupture of an Asperity: 3. Superposition



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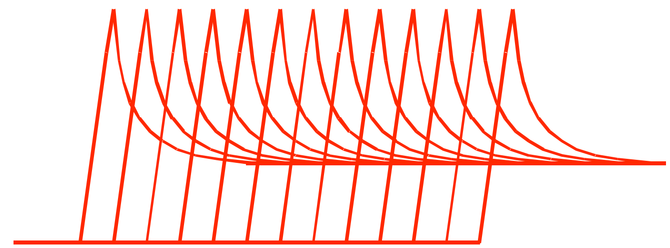
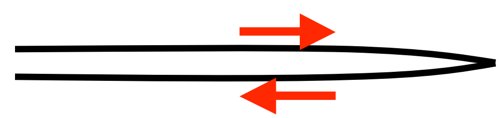


Non-radiating steady state rupture

+

Extra stress drop applied behind moving crack



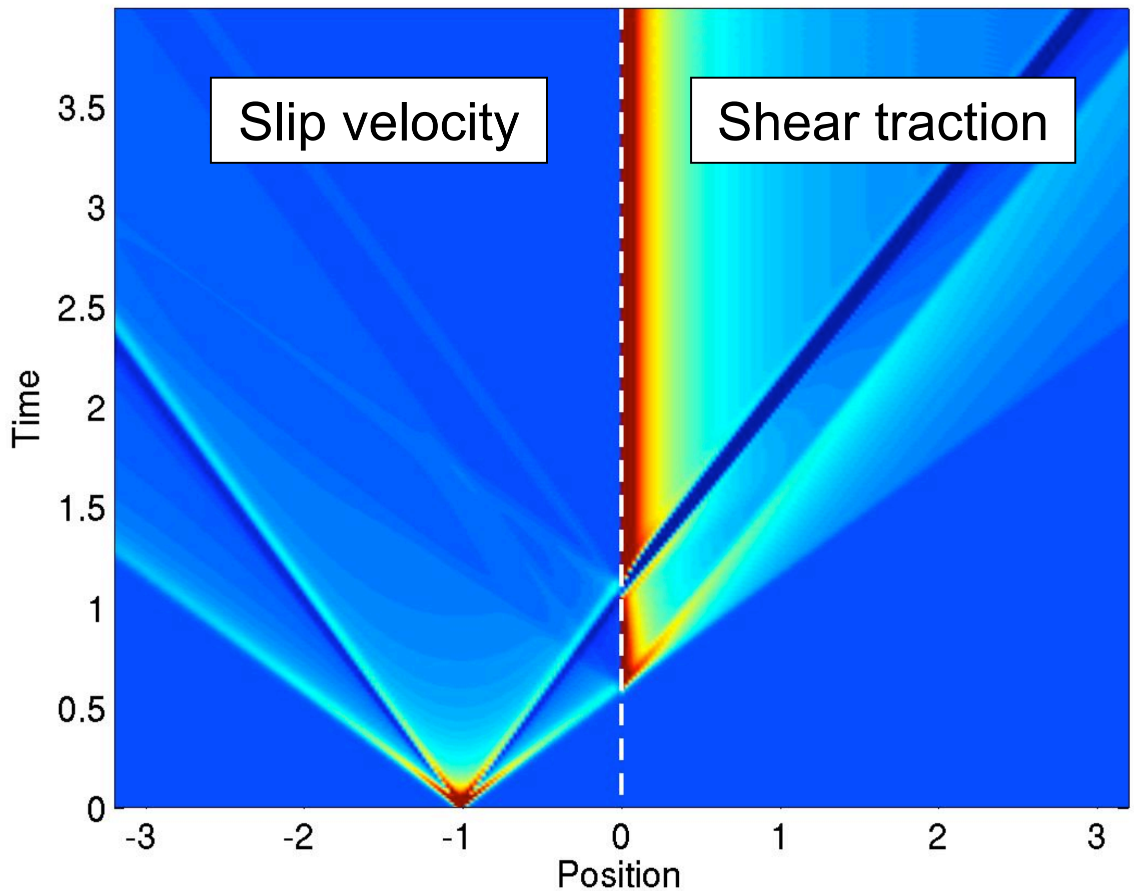
(Radiating transient diffraction problem)

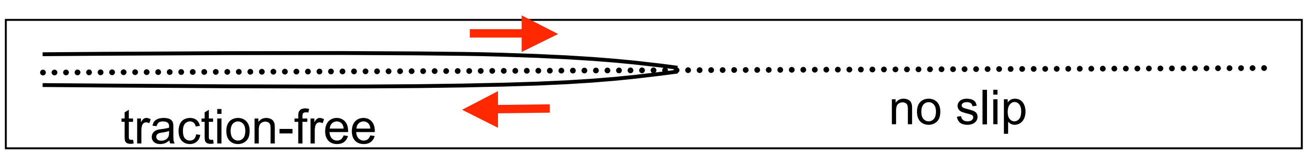
Note: Superposition only works when assuming constant rupture speed.

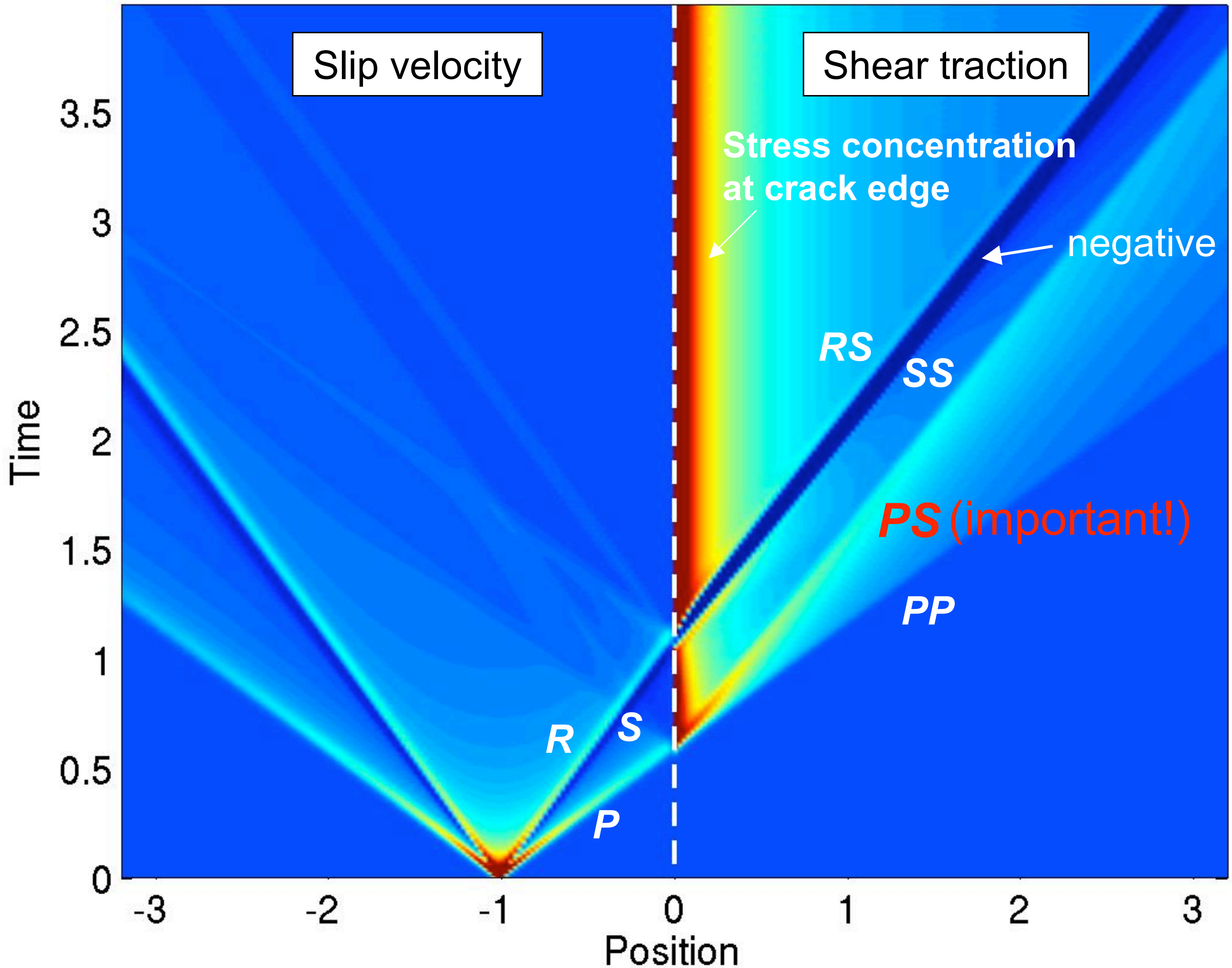
Relax this condition by determining the dynamics with a friction law

Transient waves will drive rupture at faster (even supershear) speeds

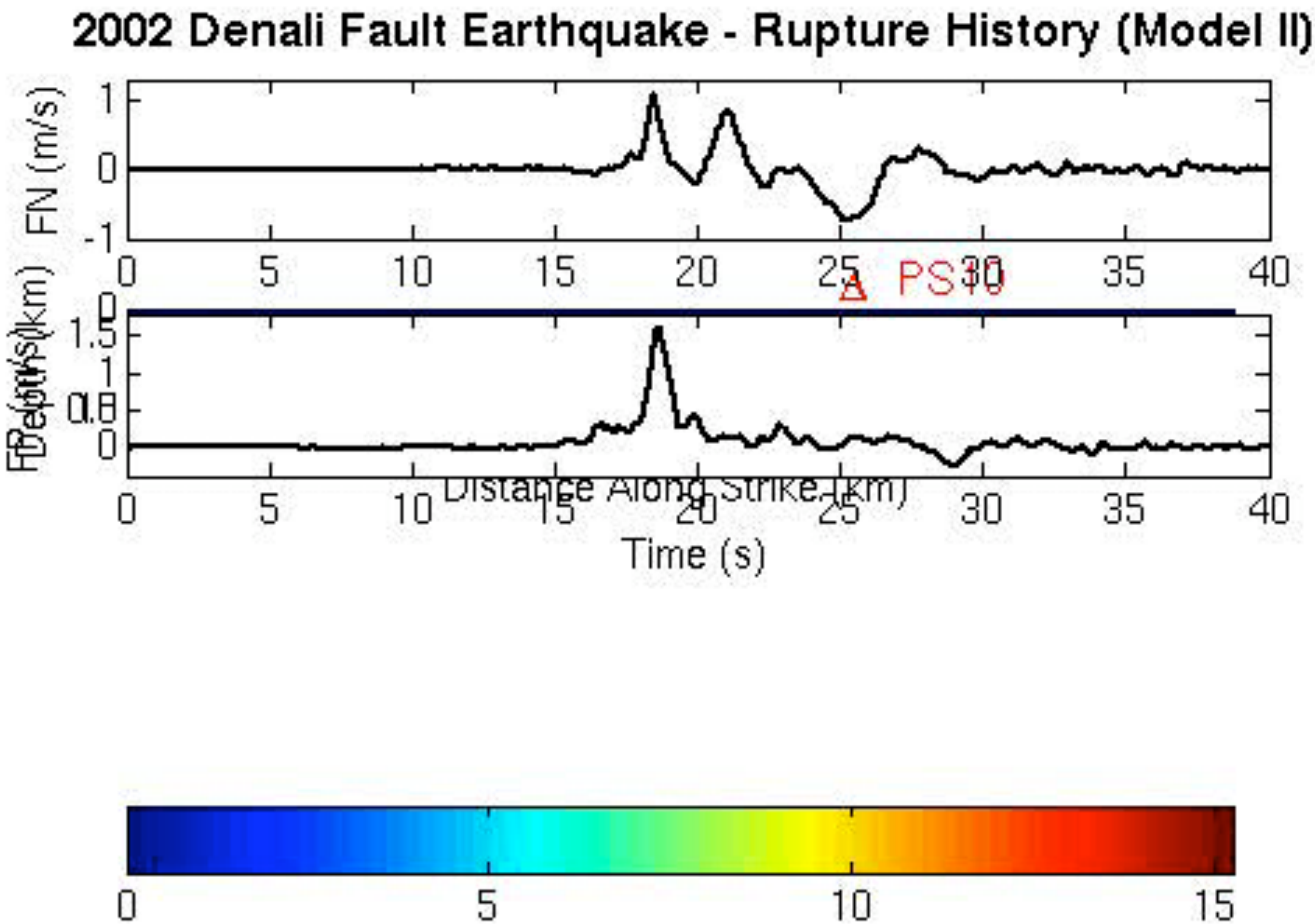
Transient Diffractions:
Step-function Stress Drop Behind Stationary Crack

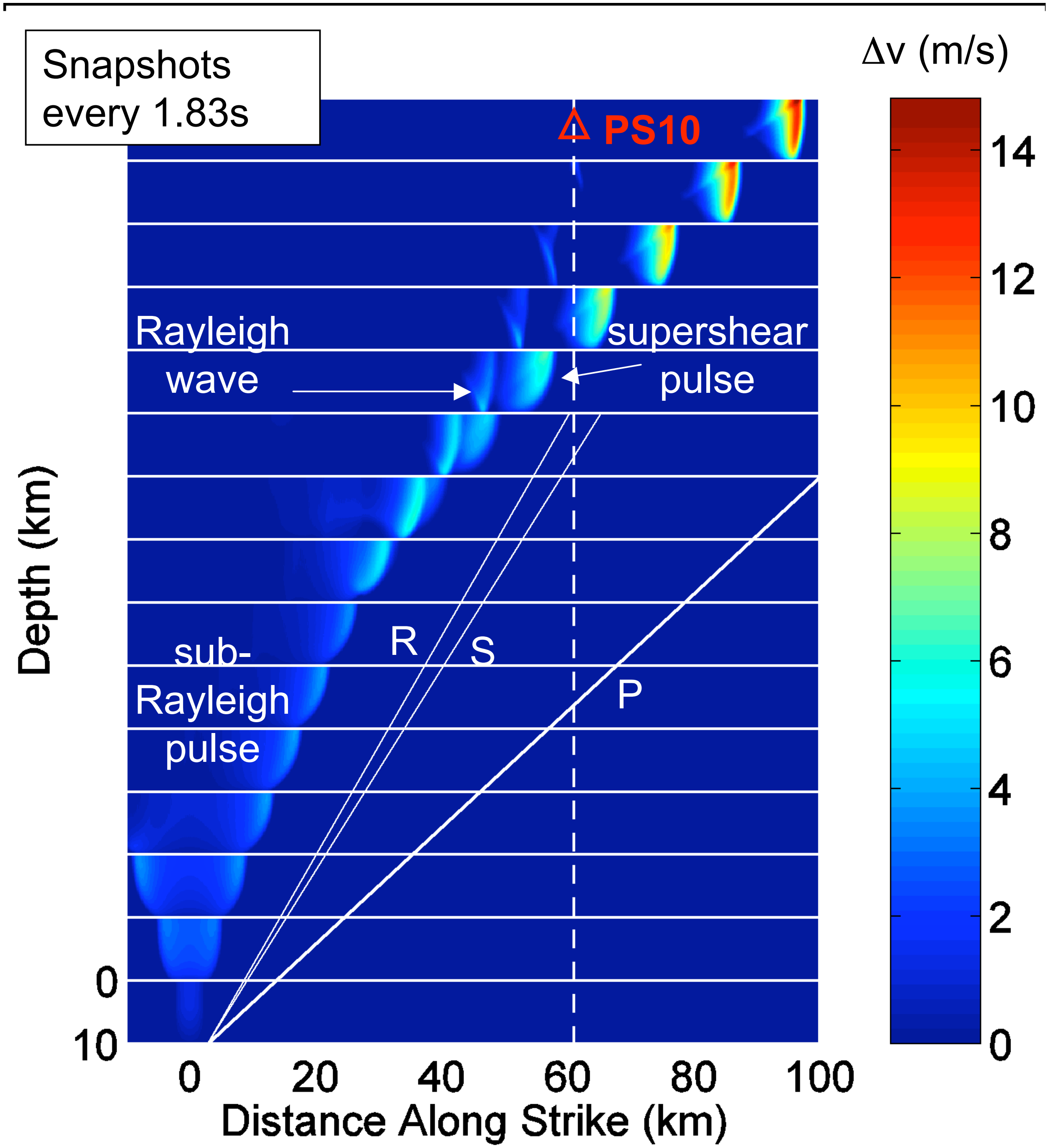




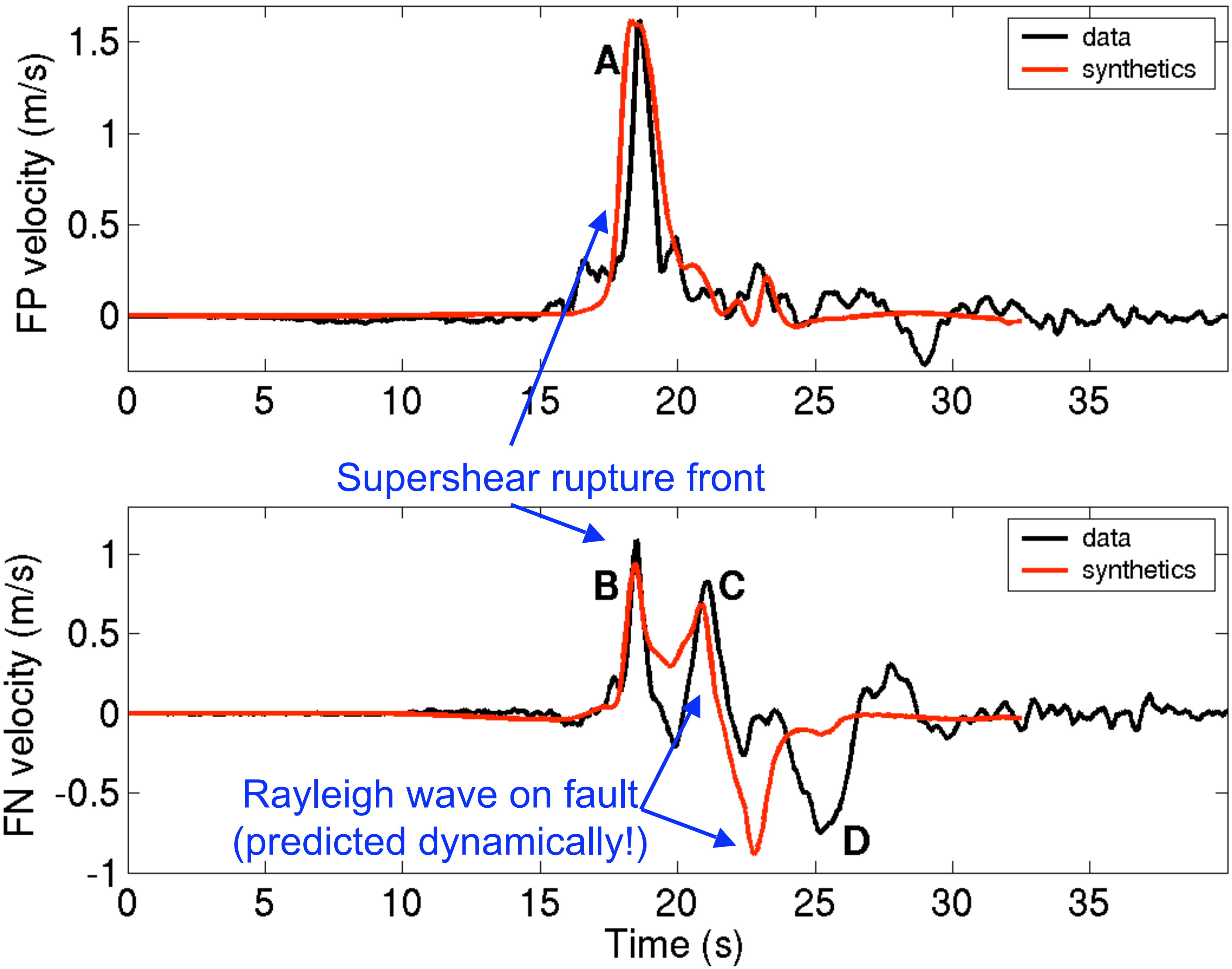


Slip velocity
Shear traction
Stress concentration
at crack edge
negative
RS
SS
PS (important!)
PP
R
S
P
Time
Position
3.5
3
2.5
2
1.5
1
0.5
0
-3
-2
-1
0
1
2
3


2002 Denali Fault Earthquake - Rupture History (Model II)
FN (m/s)
FP (m/s)
Depth (km)
PS10
Distance Along Strike (km)
Time (s)

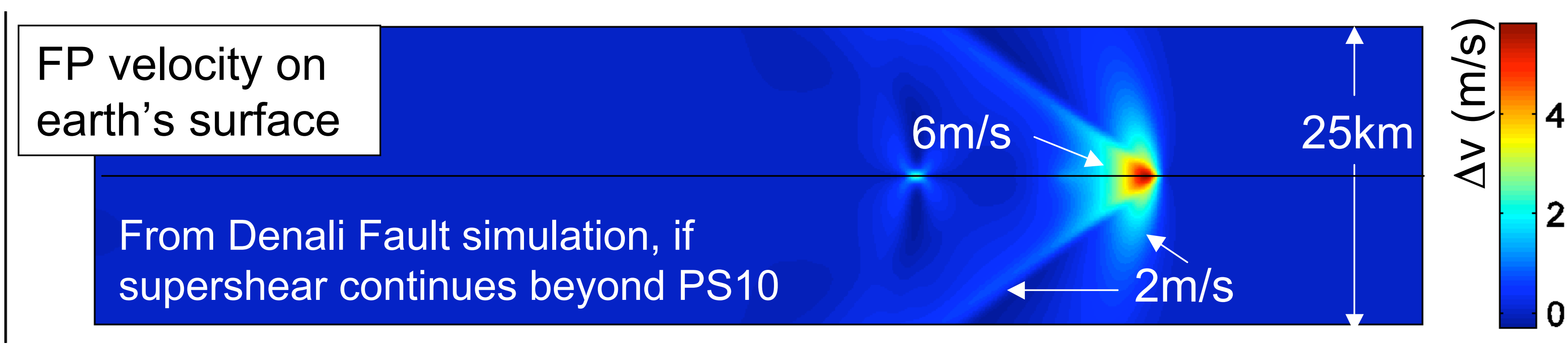


(Dunham and Archuleta, *BSSA*, 2005)


FP velocity (m/s)
1.5
1
0.5
0
0
5
10
15
20
25
30
35
A
data
synthetics
Supershear rupture front
FN velocity (m/s)
1
0.5
0
-0.5
-1
B
C
D
data
synthetics
Rayleigh wave on fault
(predicted dynamically!)
Time (s)

Conclusions

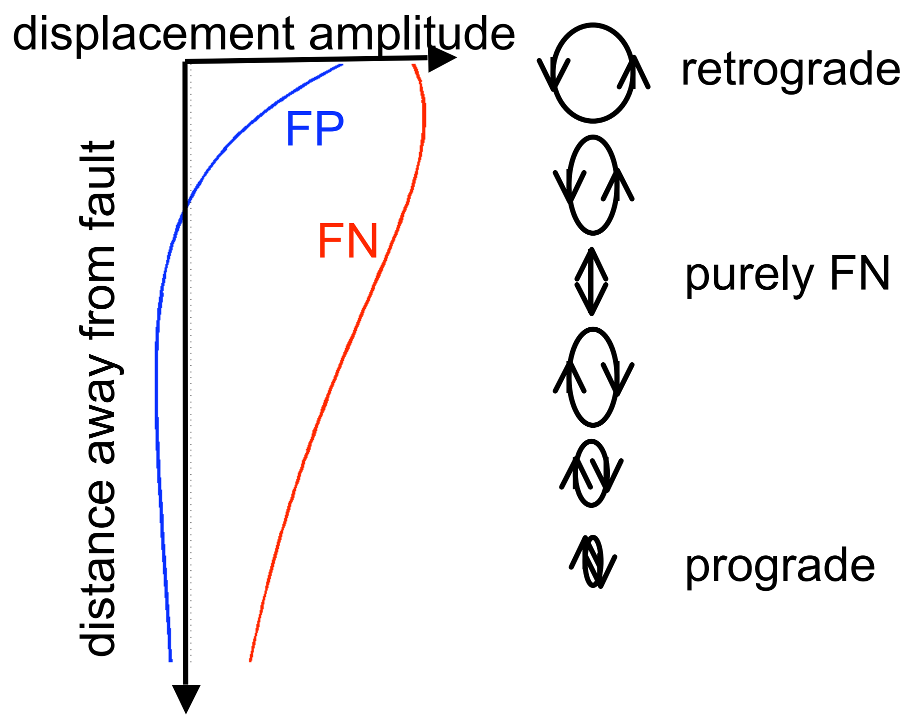
- Supershear ruptures do occur in nature
  - Denali Fault: 30km before PS10 to 30km after PS10
  - Have we really seen everything in only 50 years?
- Supershear records contain exact record of fault slip history
- Supershear generates large velocities far off of fault
  - Cause of extensive damage in Turkey?
  - Bay Bridge engineers already concerned about FP
  - Do our current design standards take this into account?



Why is the Rayleigh wave absent from FP?

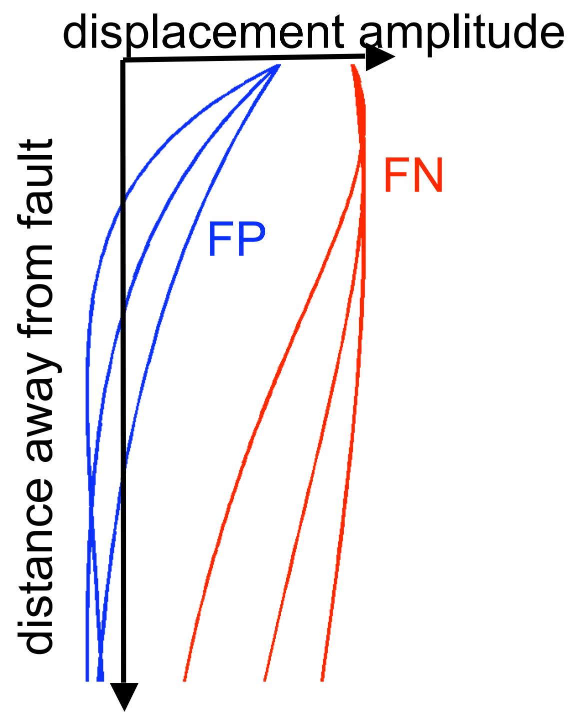
What we observe is a *pulse* (i.e., a superposition of harmonic Rayleigh waves of various wavelengths)

Examine harmonic Rayleigh wave (length scale is wavelength):



Why is the Rayleigh wave absent from FP?

Superposition of various wavelengths causes destructive interference of FP (but not FN) component!



(pointed out by Michel Campillo)

Characterizing the Excited Waves

Decompose displacement field

$$u = u^p + u^s$$

$$\left(-\frac{1}{c_p^2}\frac{\partial^2}{\partial t^2} + \nabla^2 \right) u^p(t,x,y) = 0 \qquad \nabla \times u^p = 0$$

Dilatational

$$\left(-\frac{1}{c_s^2}\frac{\partial^2}{\partial t^2} + \nabla^2 \right) u^s(t,x,y) = 0 \qquad \nabla \cdot u^s = 0$$

Shear

Excitations as Plane Waves

Solutions of governing (wave) equations are just plane waves $$e^{i(k_x x + k_y y - \omega t)}, \omega = kc$$

Let's parameterize them by

1. Along-fault phase velocity ω / k_x
2. Along-fault wavelength $2\pi / k_x$

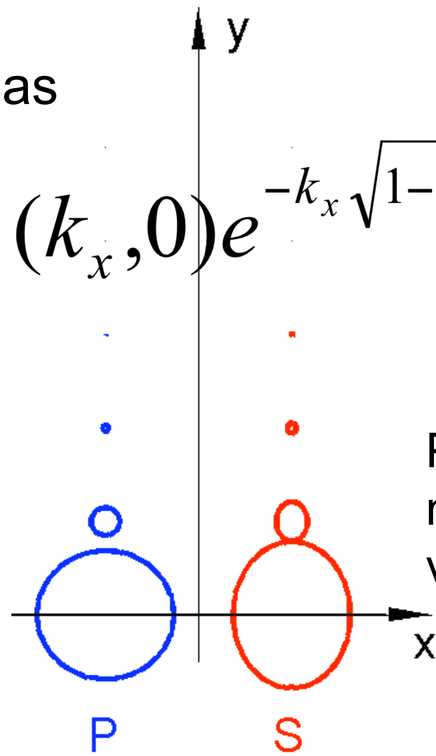
Steady-state motion along fault requires

$\omega / k_x = V$ (steady-state velocity)

Inhomogeneous Waves (V<c)

Fields decay off fault as

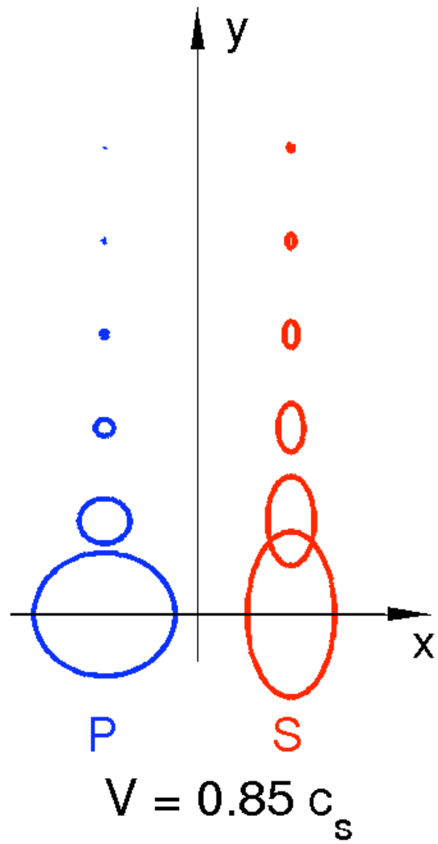
$$u^p(k_x, y) = u^p(k_x, 0)e^{-k_x\sqrt{1-(V/c_p)^2}\,y}$$



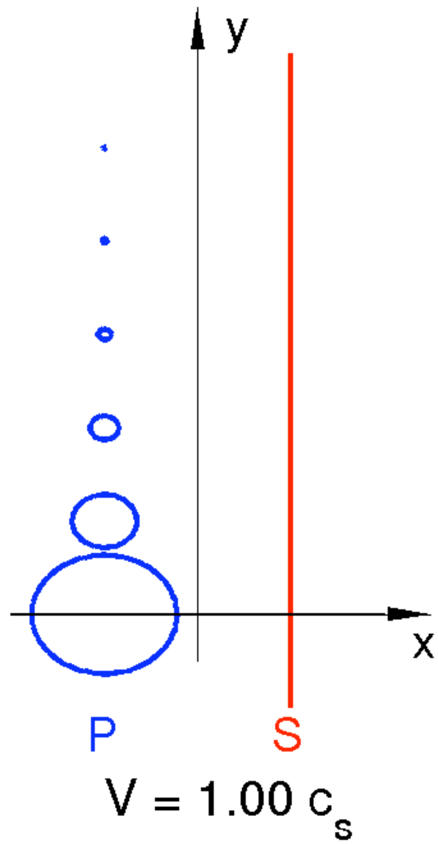
Particle motion at various y

1. High frequency information is quickly lost as observation point moves away from fault
2. No far field radiation

Inhomogeneous Waves (V<c)

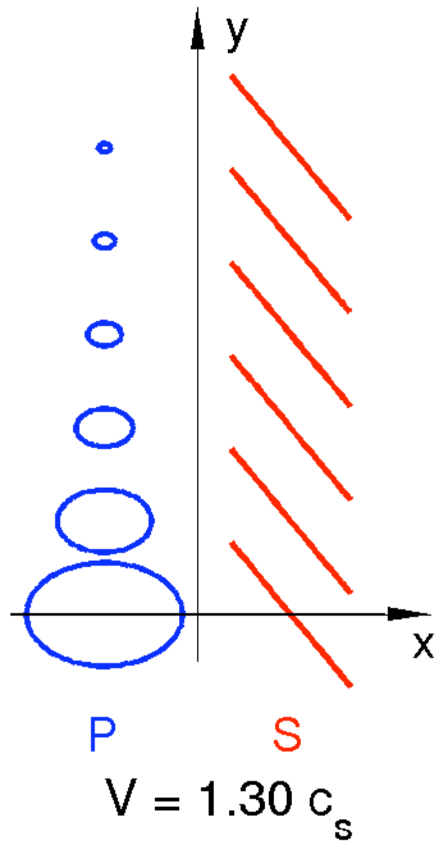


Inhomogeneous P wave + Grazing S wave

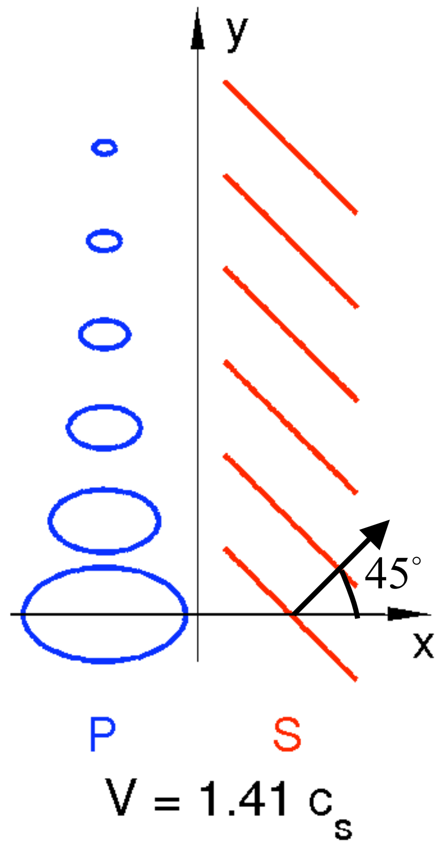


S waves start to radiate (amplitude independent of y)

Inhomogeneous P wave + Grazing S wave



Inhomogeneous P wave + Grazing S wave

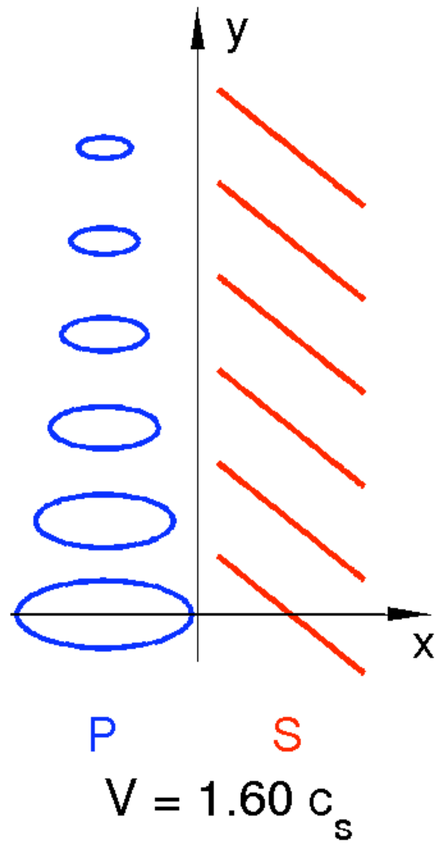


At $V = \sqrt{2}c_s$
FP and FN exactly balance for S waves ➔

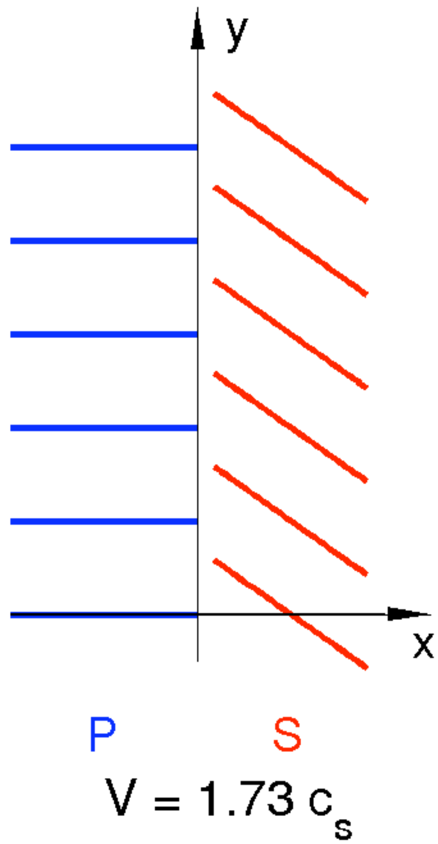
No excitation of S waves

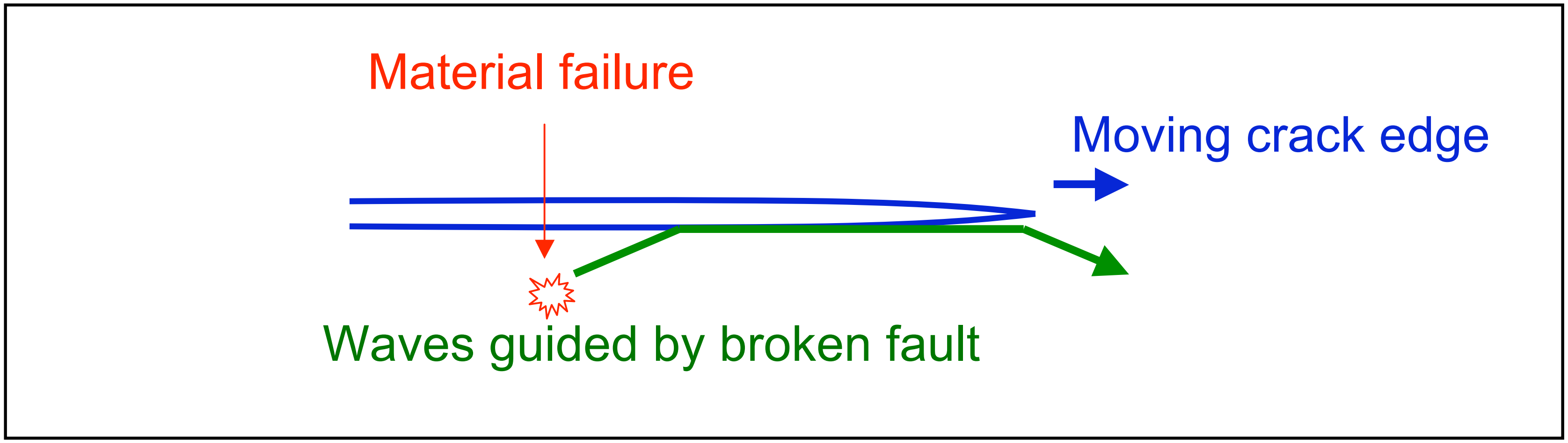
$$\sigma_{xy} = \mu\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) = \mu\left(ik_y u_x + ik_x u_y\right) = 0$$

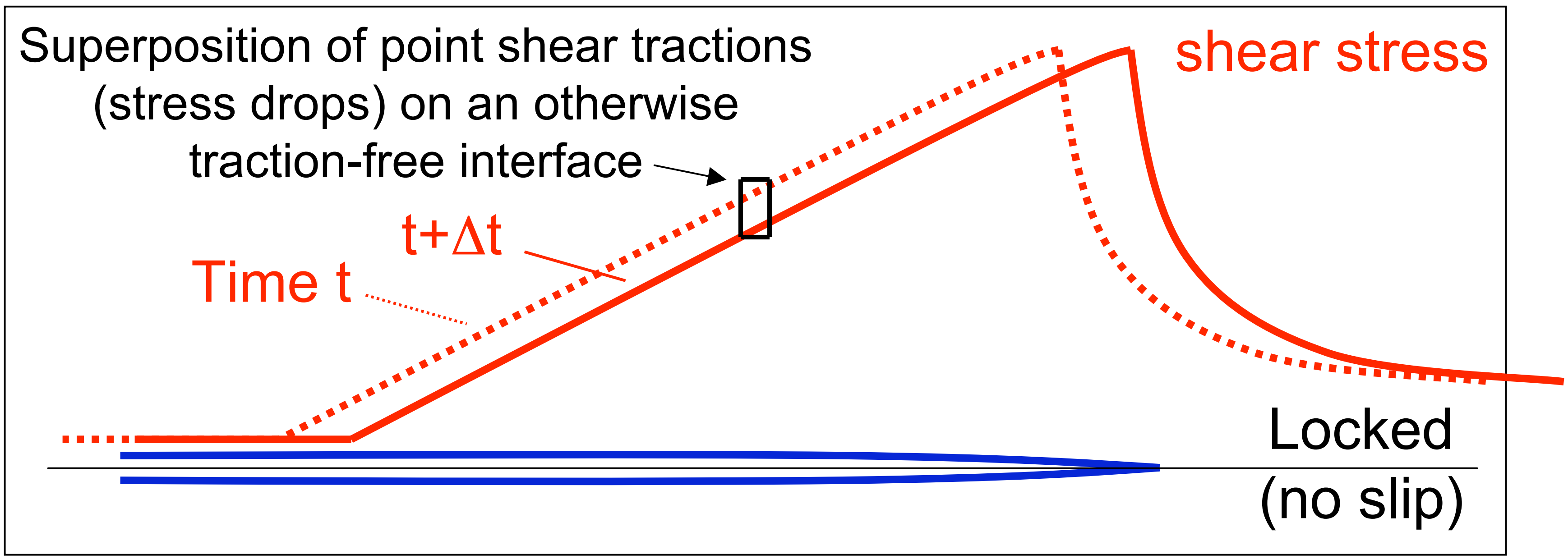
Inhomogeneous P wave + Grazing S wave



Grazing P wave + Radiating S wave

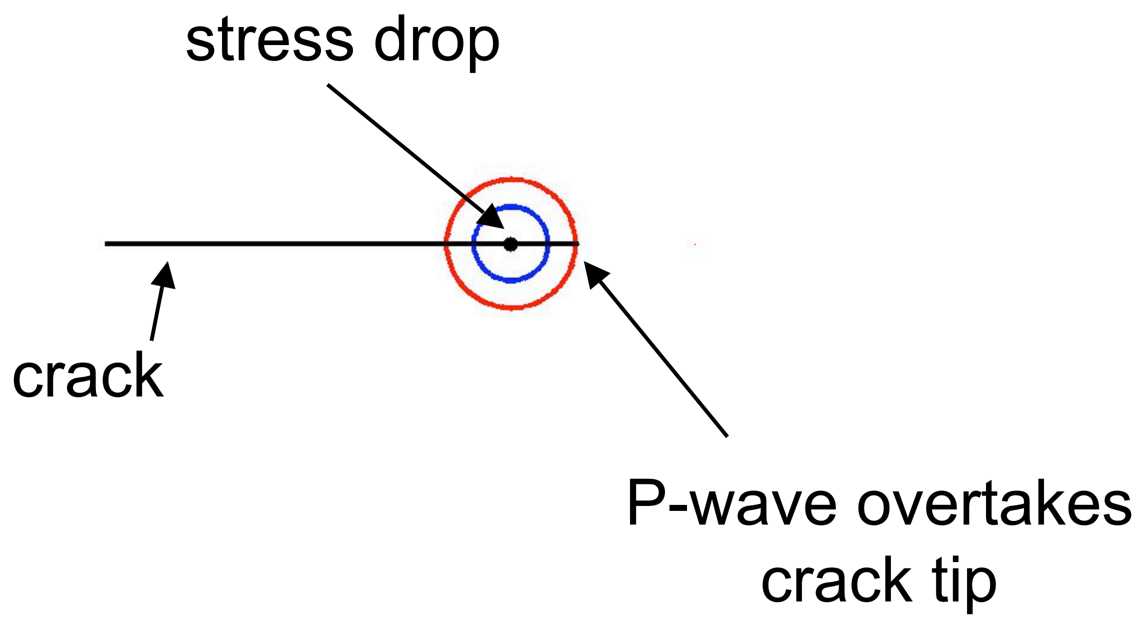



Material failure
Moving crack edge
Waves guided by broken fault

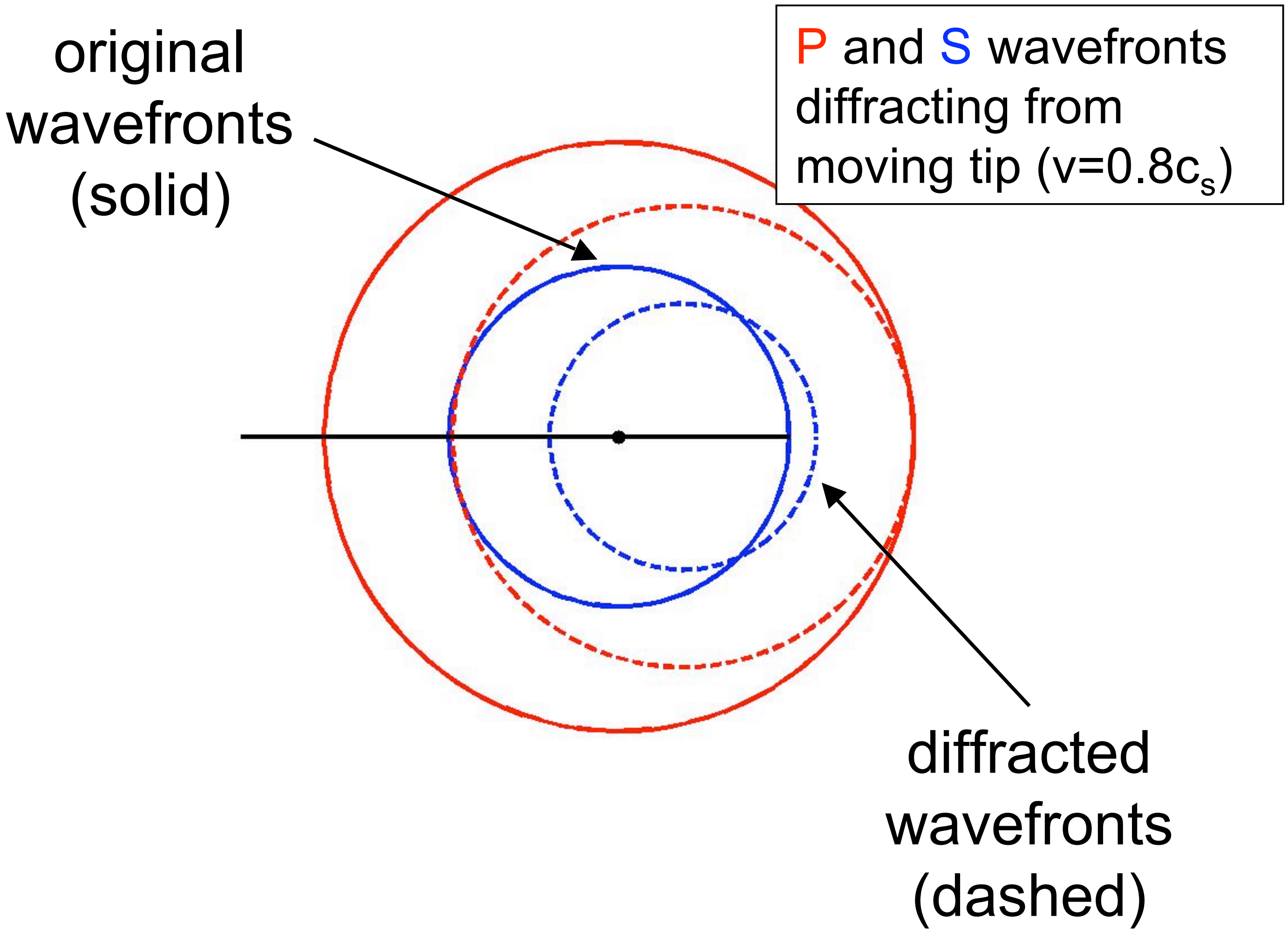

Superposition of point shear tractions
(stress drops) on an otherwise
traction-free interface
shear stress
t+Δt
Time t
Locked
(no slip)

Crack Edge Diffraction

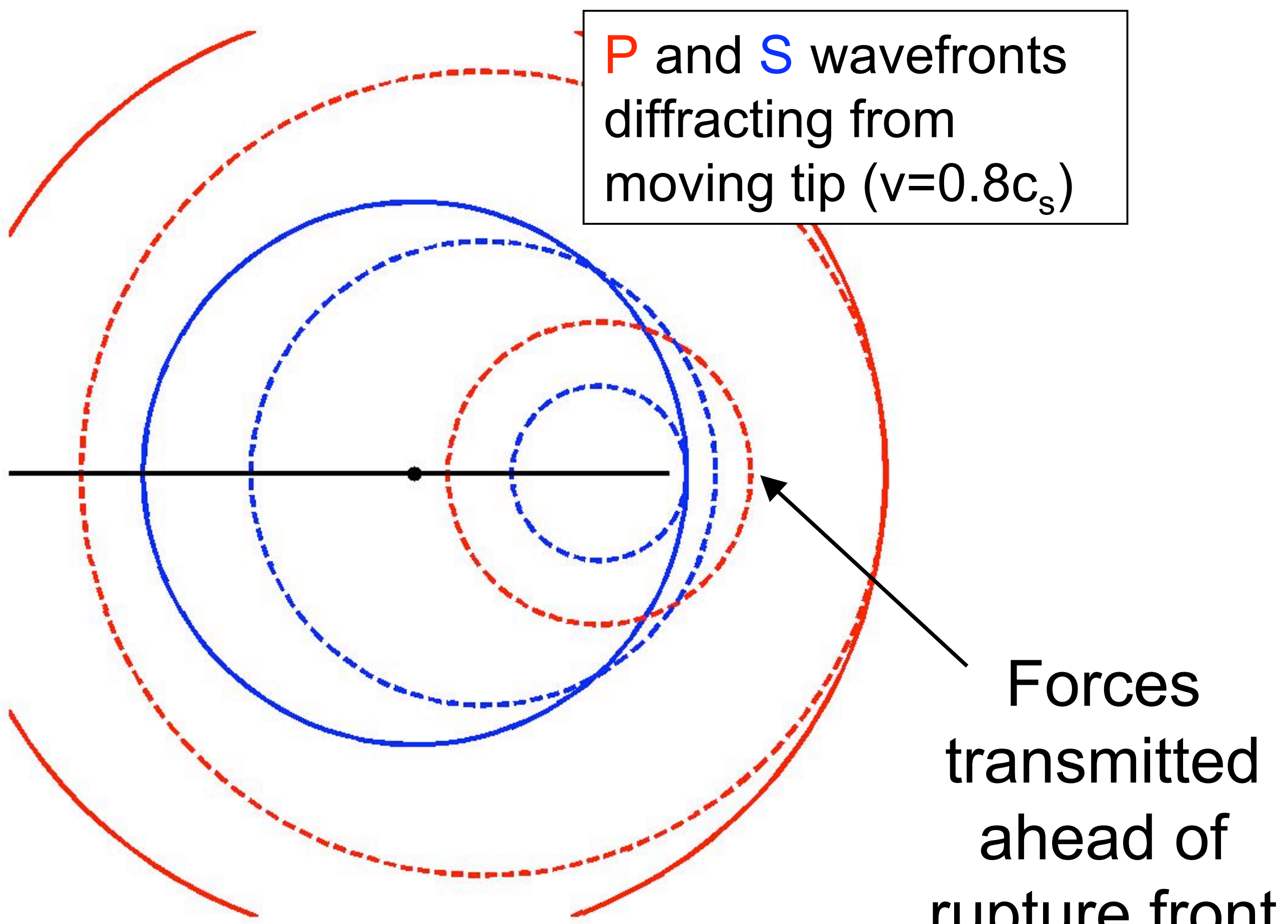
P and S wavefronts diffracting from moving tip ($v=0.8c_s$)



Crack Edge Diffraction

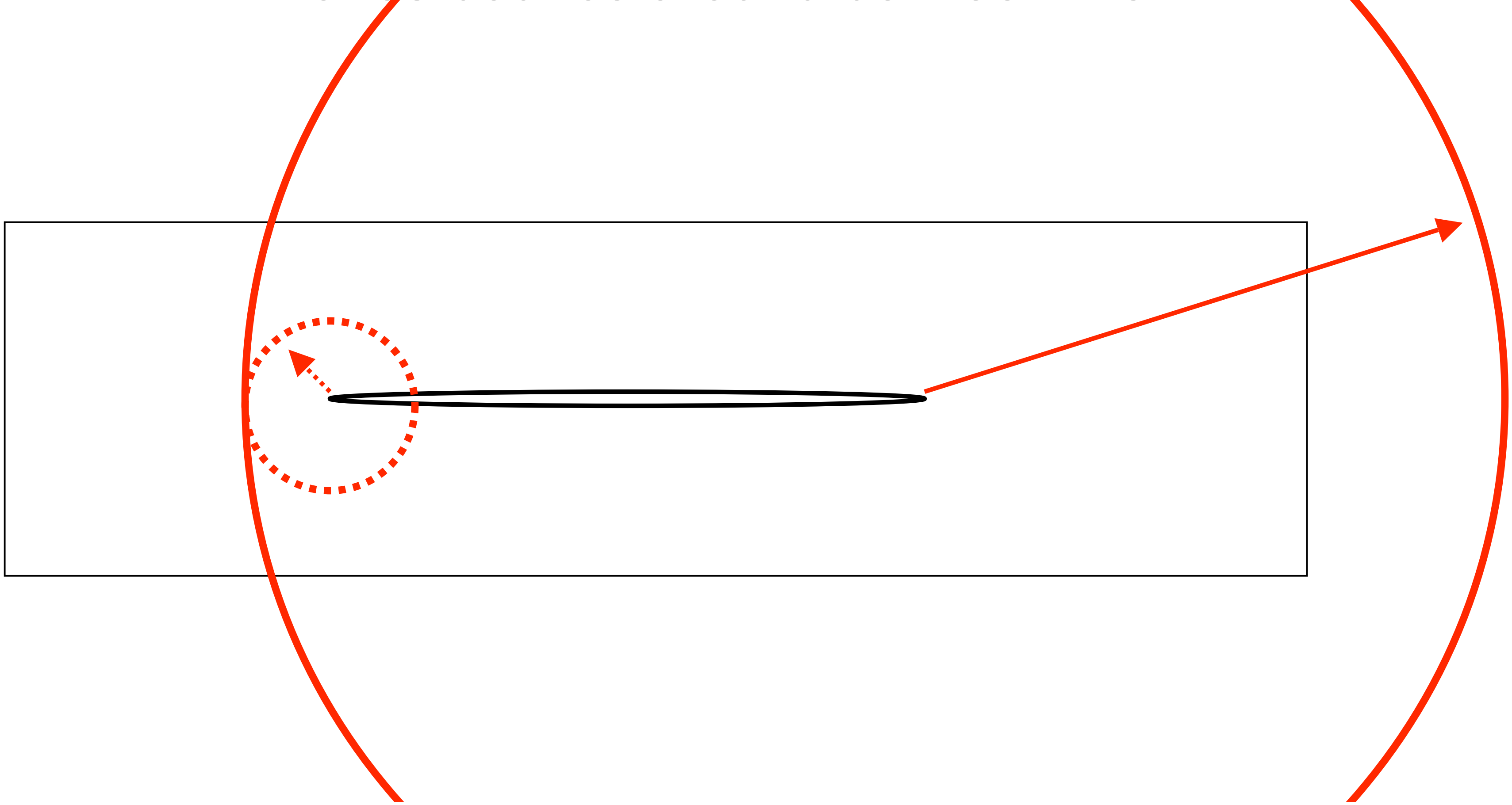


Crack Edge Diffraction

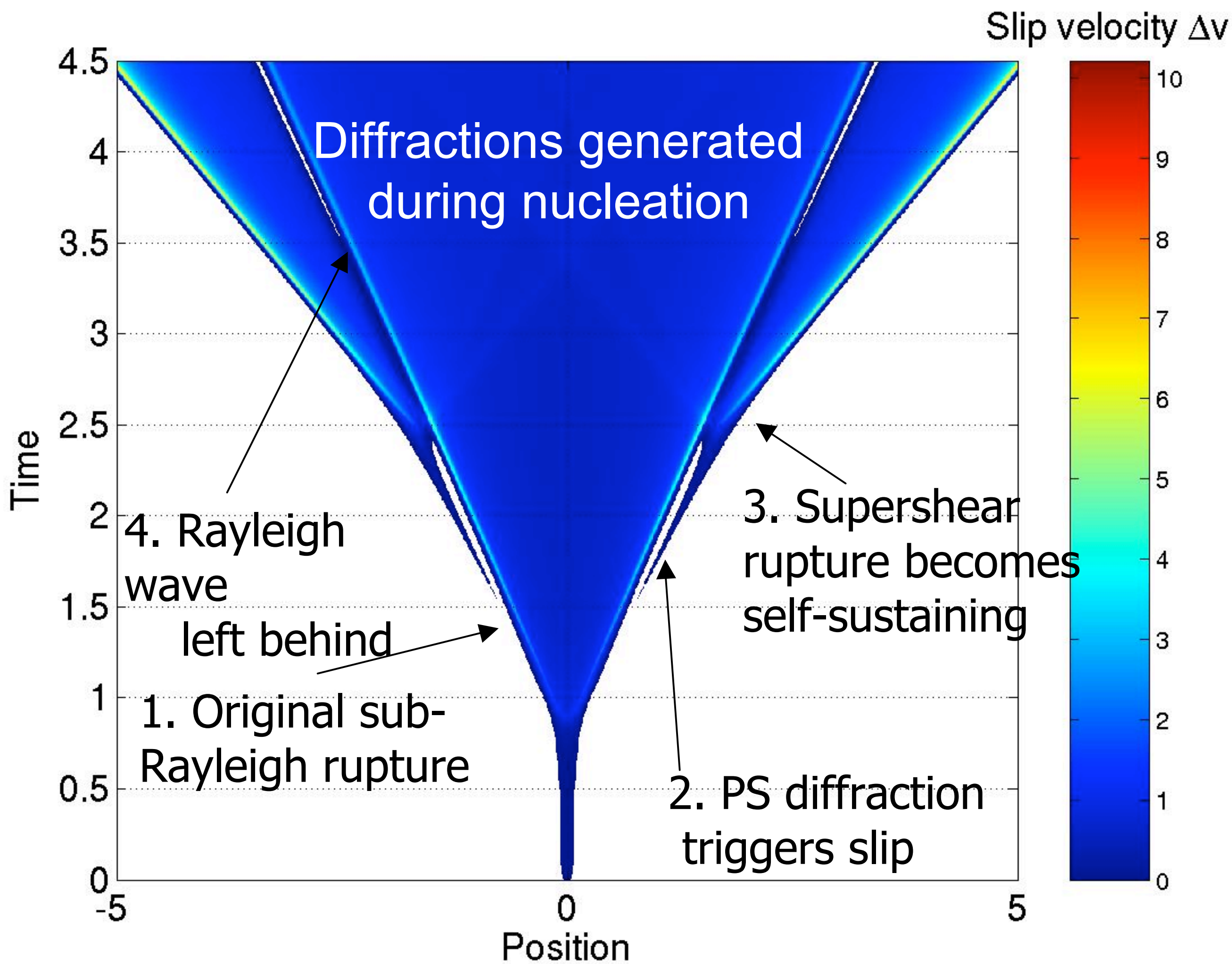


Nucleation

During nucleation, crack tips are close together and waves bounce around between them



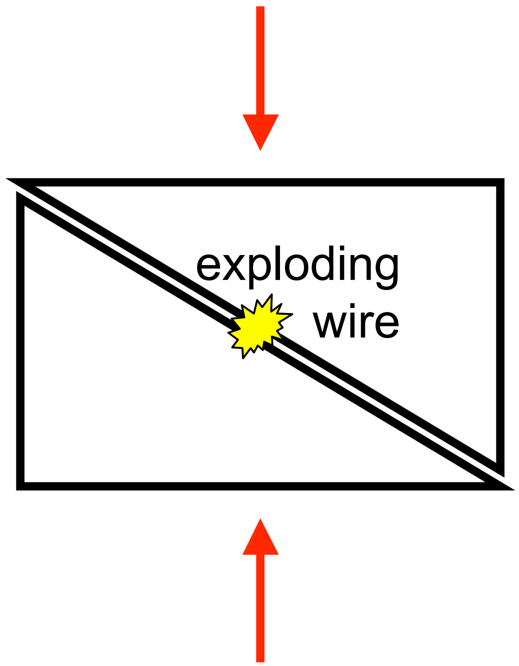
Multiple Diffractions Between Crack Tips

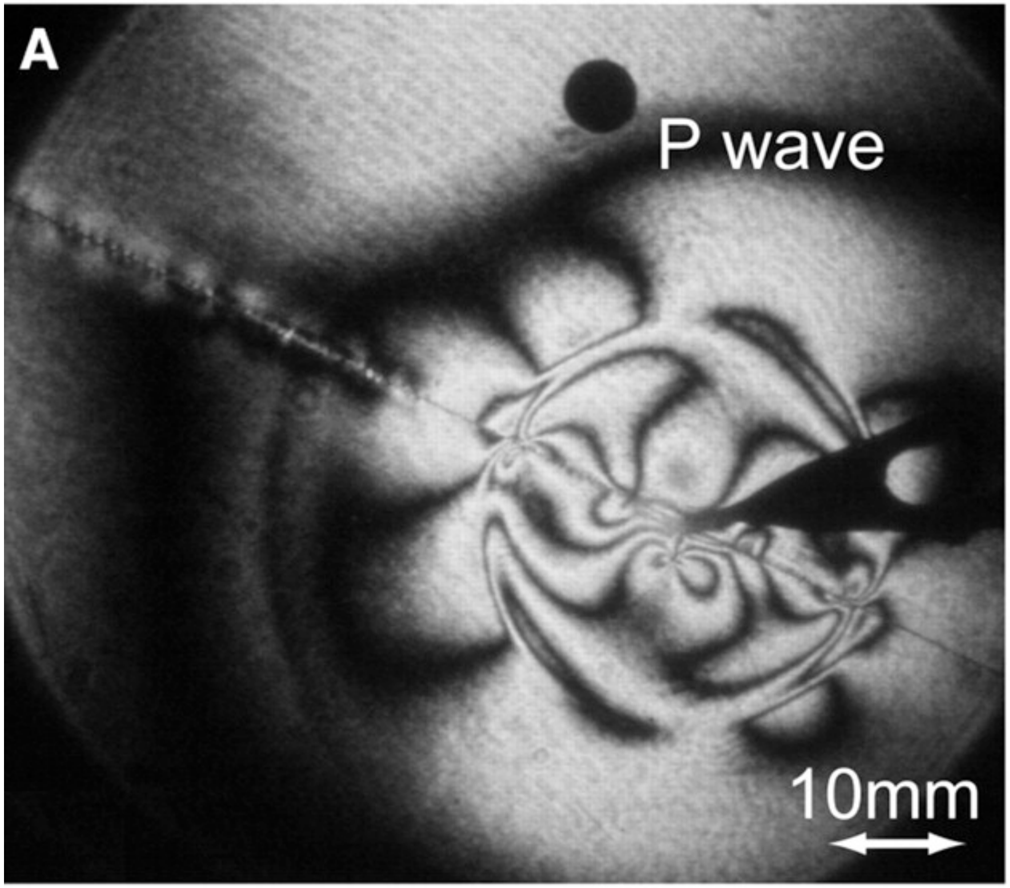


Predicted theoretically by Burridge (1973) and observed numerically by Andrews (1976)

Experimental Observation

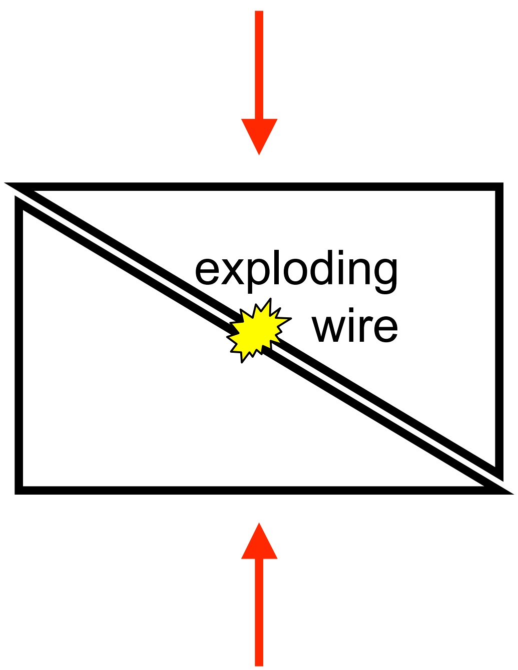
Laboratory experiments of Xia and Rosakis (2004)

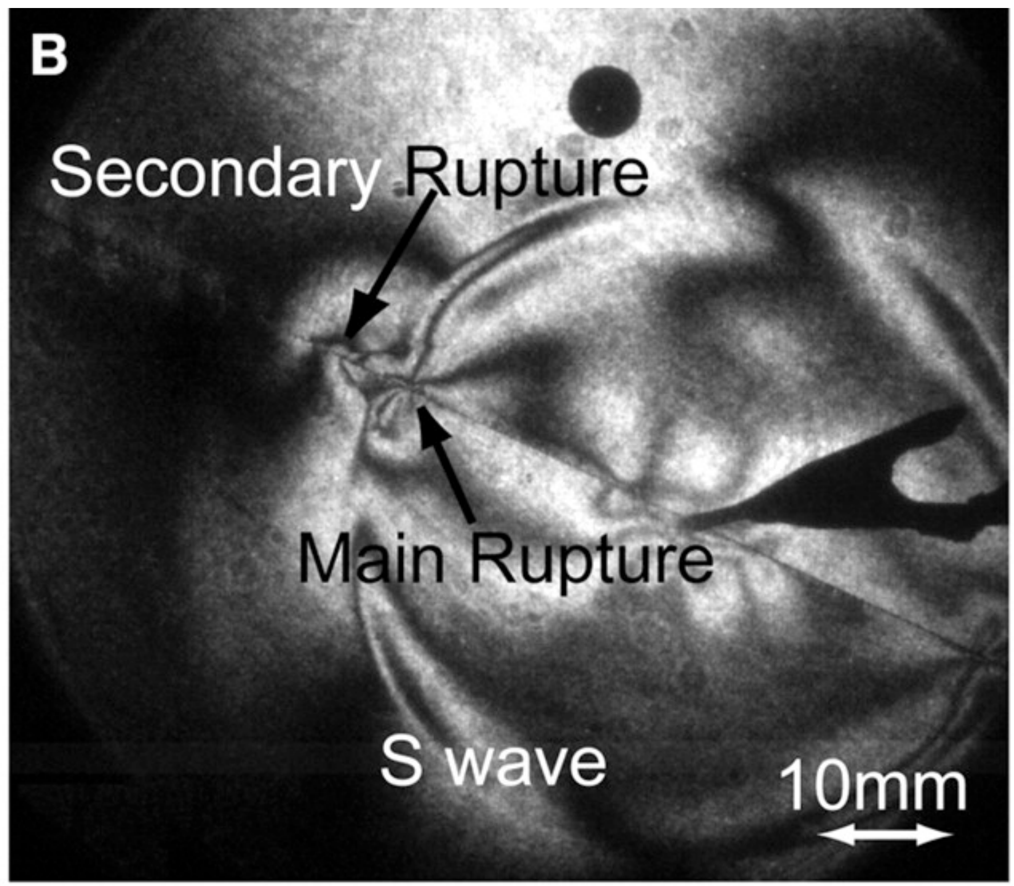




Experimental Observation

Laboratory experiments of Xia and Rosakis (2004)





Experimental Observation

Laboratory experiments of Xia and Rosakis (2004)